MINNESOTA GEOLOGICAL SURVEY

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REVISED KEWEENAWAN SUBSURFACE STRATIGRAPHY, SOUTHEASTERN MINNESOTA

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REVISED KEWEENAWAN SUBSURFACE STRATIGRAPHY, SOUTHEASTERN MINNESOTA

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by

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ABSTRACT

The Midcontinent Gravity High is the major tectonic feature of the northern midcontinent region. Numerous geophysical surveys have shown that this structure is mainly a sequence of basaltic lava flows which form steep-sided, en echelon blocks, on the average about 40 miles wide and several miles thick. Clastic rocks occur in graben-like flanking basins and in axial basins on top of the blocks. Of particular interest are the sedimentary rocks of Keweenawan age that flank and overlie the St. Croix horst, an uplifted basalt block in east-central and southeastern Minnesota. Because of their red color, these sandstones and shales have been grouped together under the name "Red Clastic Series," a "temporary" term first proposed in 1911. However, a detailed study of approximately 4,000 feet (1,220 meters) of diamond drill core from a number of localities has demonstrated the presence of at least three distinct lithic units which can be traced laterally for some distance. Accordingly, it is recommended that the name "Red Clastic Series" be abandoned and replaced by a more suitable nomenclature. The three Keweenawan formations recognized in the subsurface are: (1) Hinckley Sandstone, a buff to tan rock containing 95 or more percent quartz; (2) Fond du Lac Formation, consisting of intercalated moderate red shale and reddish-brown sandstone containing quartz, orthoclase, microcline, sodic plagioclase and "granitic" rock fragments; and (3) Solor Church Formation, a newly named formation consisting of dark reddish-brown mudstone and pale reddish-brown sandstone, containing variable amounts of quartz, plagioclase of intermediate composition (oligoclase-andesine), and aphanitic rock fragments. The first two formations are named from surface exposures; however, the Solor Church Formation, so far as is known, is confined entirely to the subsurface.

A stratigraphic analysis indicates that, in the flanking basins, the Solor Church Formation is overlain unconformably by the Fond du Lac Formation, which in turn is gradationally overlain by the Hinckley Sandstone. In contrast, the Solor Church Formation overlies basaltic rocks on top of the horst and in turn is unconformably overlain by the Hinckley Sandstone; at places a regolith separates the two formations. Either the Fond du Lac Formation was never deposited on top of the horst, or it was removed prior to the time of Hinckley deposition.

INTRODUCTION

For almost 100 years it has been known that a considerable thickness of red sandstone and shale of probable Late Keweenawan age lies beneath the Paleozoic sedimentary rocks in southeastern Minnesota (Winchell and Peckham, 1874, p. 79; Winchell, 1876, p. 187). For almost as long, these redbeds have been correlated with rocks of similar appearance that crop out along the south shore of Lake Superior (Winchell, 1885, p. 54). The redbeds comprise a large proportion of the total sedimentary rock sequence in southeastern Minnesota. For example, in the vicinity of the Twin Cities, they are inferred to be at least 4,000 feet (1,220 meters) thick (Sims and Zietz, 1967), whereas the overlying Paleozoic rocks are about 1,000 feet (305 meters) thick (Thiel and Schwartz, 1941). Over the years, many "deep wells" have penetrated the Paleozoic cover (fig. 1), but very little detailed information about the Keweenawan sedimentary rocks is available. Although some very fine descriptions and well logs exist, these rocks for the most part have merely been collectively referred to as hundreds of feet of undivided red sandstone or shale.

In 1965 and 1966 a search for reservoirs suitable for the underground storage of natural gas resulted in the drilling of a number of test wells in southeastern Minnesota (fig. 1). Many of these test wells penetrated extensive thicknesses of Keweenawan sandstone and shale, and so far as is known, the recovered core material represents the most complete subsurface record of these strata ever obtained. The purpose of this report is to: (1) demonstrate that the redbed sequence can be divided into several stratigraphically significant lithic units; (2) define a new lithostratigraphic unit, the Solor Church Formation, for one of the intervals; and (3) record and summarize in a single place the diverse data obtained during this study, and integrate these data with previously known data so as to provide a better insight into the sedimentary and tectonic history of the Keweenawan System in southeastern Minnesota.

STRATIGRAPHIC NOMENCLATURE AND HISTORY OF PREVIOUS RESEARCH

Only a few scattered outcrops of Upper Precambrian sedimentary rocks occur in Minnesota. The term "Fond du Lac Formation" was used by Upham (1884) to describe dark-red arenaceous shales and reddish-brown arkosic sandstones exposed along the St. Louis River, southwest of Duluth (fig. 1). The Fond du Lac Formation is overlain transitionally to the south by a yellowish-gray to nearly white, quartzose sandstone that Winchell (1886, p. 337; 1888, p. 286) named the Hinckley Sandstone, from typical exposures near the city of Hinckley (fig. 1).

The first specific reference to the red sedimentary rocks in the subsurface of southeastern Minnesota is found in the account by Winchell and Peckham (1874) of the drilling of a "salt" well at Belle Plaine (fig. 1). Winchell later (1876) described similar rocks from another well drilled at east Minneapolis and correlated the red sandstone encountered there with that found in the Belle Plaine well. Shortly thereafter, redbeds from other "deep wells" were described by Hall (1883) and Meads (1891). None of these workers, however, used any specific names when referring to these sedimentary rocks.

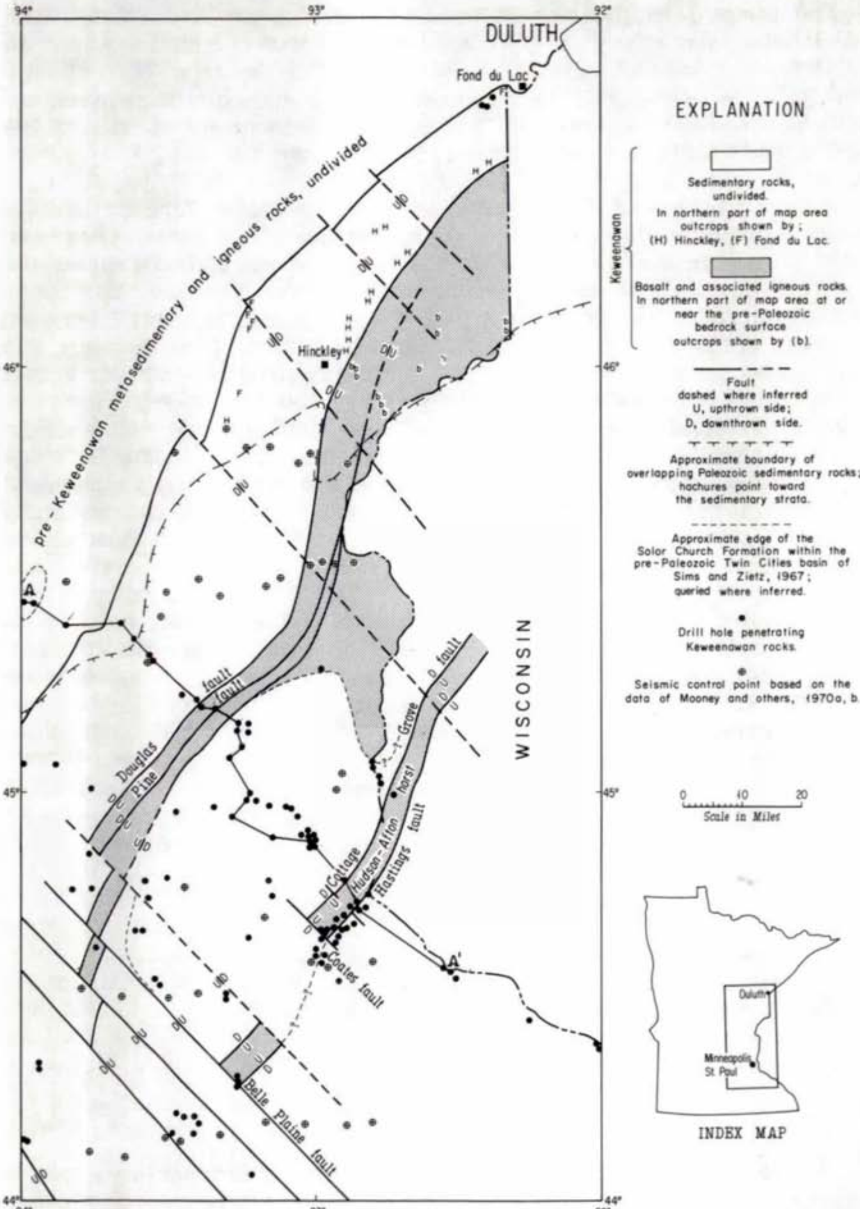


Figure 1 — Generalized bedrock geologic map of east-central Minnesota and the inferred distribution of sub-Paleozoic rocks in southeastern Minnesota (modified from Sims and Zietz, 1967).

Generally, it has been assumed that the rocks exposed at Fond du Lac are correlative with the redbeds beneath the Hinckley or directly beneath Paleozoic rocks in southeastern Minnesota (e.g. Crowley and Thiel, 1940). However, Hall and others (1911) concluded that any correlation based on color alone was tenuous, and therefore introduced the term "Red Clastic Series" (p. 33) as an informal name to describe the red-colored sedimentary rocks which occur ". . . between the crystalline basement rocks and the recognizably fossiliferous Upper Cambrian formations. . ."

Since that time, a dual system of nomenclature — Fond du Lac for surface exposures and "Red Clastics" for subsurface occurrences — has been used in Minnesota and elsewhere in the Middle West, and in general the terms have come to be used interchangeably. For example, the terms "subsurface Fond du Lac" or "lower Fond du Lac" commonly have been used in southeastern Minnesota (e.g., Craddock and others, 1963; Mooney and others, 1970a), and the name "Fond du Lac" has been applied to redbeds that occur as far away as southern Illinois (Workman and Bell, 1948). However, Kirwin (1963) demonstrated, using variations in mineralogic composition, that the Red Clastics could be subdivided into five lithostratigraphic intervals and sugggested that only one interval is mineralogically equivalent to the Fond du Lac Formation at its type locality. The results of my study substantiate the broad conclusions outlined by Kirwin (1963). Most of the "redbeds" described here contain abundant sand-size grains of basalt and plagioclase, whereas the Fond du Lac Formation contains abundant orthoclase, microcline, and "granitic" rock fragments and only minor amounts of sand-size basalt fragments and plagioclase. In turn, rocks with abundant basaltic detritus have a bulk density of around 2.6 to 2.7, a value much higher (tbl. 1) than that of around 2.3 reported for the Fond du Lac and Hinckley formations (Thiel, 1956; Craddock and others, 1963), and consequently a higher seismic velocity (Halls, 1969; Mooney and others, 1970a). For these reasons, it seems advisable to discontinue use of the term "Red Clastic Series," and to recognize a new lithostratigraphic unit, the "Solor Church Formation." This formation includes all the red sandstone, shale, and associated rocks in the subsurface of southeastern Minnesota that are lithologically distinct from the Fond du Lac Formation. The Solor Church Formation, as here defined, may be subdivided into several smaller lithologic intervals which may prove, with additional study, to be of formational status as well; however, because the lateral continuity of these smaller lithological intervals cannot be completely described at this time, they are retained here as informal units for convenience in discussion. The correlation of previous nomenclature with that used in this report is summarized in Table 2.

STRUCTURAL SETTING

The geographic distribution of the Keweenawan sedimentary rocks in southeastern Minnesota is closely related to the Midcontinent rift system. Knowledge of this structure in Minnesota has been greatly enhanced in recent years by several geophysical investigations, including those of Thiel (1956), Craddock and others (1963), Sims and Zietz (1967), and Mooney and others (1970a, b). The most prominent expression of the Midcontinent rift system in southeastern Minnesota is a linear gravity anomaly known as the Midcontinent Gravity High. Thiel (1956) demonstrated that the positive part of the anomaly originates from dense igneous flows of Middle Keweenawan age, and that the flanking negative anomalies result from contrasting low-

Table 1 — Some bulk-rock properties of various Keweenawan sedimentary rocks

UNIT	AVERAGE DENSITY DRY	BULK DENSITY WATER SATURATED	POROSITY IN PERCENT	SOURCE
Bayfield-Jacobsville		2.1 (+) - 2.4 (+) [(1)]	12.4 - 24.4	Halls 1969
Bayfield Group (average)		2.30 ± .063 [(2)]		Thiel, 1956
	2.26 - 2.33 [(4)] $\bar{X}$ = 2.3		11.6 - 22.6 $\bar{X}$ = 15.1	Buckley, 1898
Fond du Lac type locality		2.45	10.4 - 11.6 $\bar{X}$ = 11.0	Buckley, 1898
Waseca[(3)]	2.15 - 2.52 $\bar{X}$ = 2.3	2.41 - 2.72 $\bar{X}$ = 2.5	5.9 - 25.7 $\bar{X}$ = 20.4	This report
Oronto Group (average)		2.36 ± .119 [(1)]		Thiel, 1956
Freda - Copper Harbor		2.35 - 2.6 (+)		Halls, 1969
Solor Church Formation[(3)]	2.66	2.46 - 2.76 $\bar{X}$ = 2.73	3.3	This report

(1) 90 percent water saturated

(2) standard deviation

(3) determined by R.J. Ikola

(4) range and average value

density Upper Keweenawan sedimentary rocks. Craddock and others (1963) suggested that the Keweenawan flows were elevated several hundred to around 15,000 feet (4,570 meters) above adjacent strata to form part of what they call the St. Croix horst. Figure 1 shows the southern part of the horst in Minnesota where it is bounded on the northwest by the Douglas fault and on the southeast by the Hastings fault. Both faults are interpreted as having had steep reverse movements, and both can be traced to south of Minneapolis–St. Paul where the gravity anomalies are abruptly deflected from a northeasterly to a southeasterly direction. Comparison of the bedrock geologic map of southeastern Minnesota (Sloan and Austin, 1966) and the aeromagnetic map of southeastern Minnesota (Philbin and Gilbert, 1966) indicates that the northeast-trending magnetic anomalies terminate in the vicinity of a series of northwest-trending faults which include the Belle Plaine fault of Sloan and Danes (1962). A second positive magnetic and gravity anomaly appears some 80 miles (129 km) southeast of the anomalies associated with the St. Croix horst and indicates the presence of another northeast-trending block, which also is elevated relative to the surrounding strata. It is inferred that these and other basalt blocks along the Midcontinent Gravity High are part of a major intracontinental rift system and that their en echelon arrangement results from offsets along structures interpreted to be transform faults (King and Zietz, 1971; Chase and Gilmer, 1973).

Table 2 — Nomenclature used for Keweenawan sedimentary rocks in Minnesota and Wisconsin.

WISCONSIN			MINNESOTA		
	Thwaites, 1912 as modified by Tyler & others, 1940	Ostrom, 1967	Surface exposures Tyler & others, 1940	Sub-surface Kirwin, 1963	Sub-surface this report
Bayfield Group	Chequamegon Sst.	Chequamegon Fm.			
Bayfield Group	Devils Island Sst. (nearly pure qtz. sst.)	Devil's Island Fm.	Hinckley Sandstone >99% qtz.	Unit 1 >95% qtz., minor K-spar, no rock fragments.	Hinckley Sandstone >95% qtz.
Bayfield Group	Orienta Sandstone 75% qtz., 25% feldspar—mostly K-spar. 30% qtz., 75% feldspar—mostly plag.	Orienta Fm.	Fond du Lac Fm. 40-60% qtz., 20-25% feldspar Middle Precambrian rocks.	Red Clastic Series: Unit 2 Sst., feldspathic, grading into an arkose having 60-85% qtz. K-spar = or > plagioclase. Subordinate rock fragments.	Fond du Lac Formation
Oronto Group	Freda Sandstone <25% qtz.-75% plagioclase & aphanitic rock fragments of basaltic composition.	Freda Fm.		Red Clastic Series: Unit 3 Arkose, 50% quartz, plagioclase >>> K-spar. Subordinate rock fragments. Unit 4 30% quartz, 40% volcanic rock fragments, remainder plag.	Solor Church Formation
Oronto Group	Nonesuch Shale "Virtually unaltered debris of basic eruptives."	Nonesuch Fm.		Red Clastic Series: 5-10% quartz, remainder volcanic rock fragments and plagioclase.	Solor Church Formation
Oronto Group	Copper Harbor Conglomerate "boulder-sized conglomerate of basic eruptives."	Outer Conglomerate Fm.			
Middle Keweenawan basaltic lava flows				Middle Keweenawan basaltic lava flows	

Sims and Zietz (1967) have shown that the magnetic patterns and basalt subcrops on the southern part of the St. Croix horst delineate a basin which underlies and conforms approximately in outline to the Twin Cities basin in overlying Paleozoic strata (Thiel and Schwartz, 1941; Mossler, 1972). Previously published geophysical evidence, combined with drilling data described in this report, indicates that a narrow strip of basalt on the east side of the basin is in fault contact with Upper Keweenawan sedimentary rocks within the basin. The faulted basalt block — called the Hudson-Afton horst (Sims and Zietz, 1967) — is bordered on the west by the Cottage Grove fault, on the east by the Hastings fault, and on the southwest by the Coates fault (fig. 1).

Upper Keweenawan sedimentary rocks occur on the flanks of the St. Croix horst and within the pre-Paleozoic Twin Cities basin on the horst itself. Sedimentary rocks within the pre-Paleozoic Twin Cities basin occupy an elongated area that is at least 60 miles (97 km) long in a northeasterly direction and 30 to 35 miles (48 to 56 km) wide. Like the basalt, these clastic rocks range in thickness from a few tens to hundreds of feet on the flanks of the horst to at least 3,000 feet (910 meters) under the central part of the basin (Sims and Zietz, 1967). Keweenawan clastic rocks east of the Hastings fault are approximately 8,000 to 12,000 feet (2,440 to 3,660 meters) thick (Volz, 1968), whereas they are much thinner west of the Douglas fault.

Movement on all the above-mentioned faults was sufficiently large to place the stratigraphically older Middle Keweenawan basalts in juxtaposition with Upper Keweenawan sedimentary rocks. It has been estimated that there has been at least 8,000 to 9,000 feet (2,440 to 2,740 meters) of apparent vertical displacement on the Hastings fault, and 800 feet (244 meters) on the Cottage Grove fault (Sims and Zietz, 1967; Volz, 1968). Barazangi (1967) reports approximately 8,000 feet (2,440 meters) of apparent vertical displacement on the Coates fault.

GENERAL STRATIGRAPHY

Geographic locations of the drill holes containing Precambrian rocks evaluated in this study are shown in Figure 2. Rocks of both the Cambrian and Ordovician Systems overlie the Precambrian strata in this area. The Cambrian strata are a little over 700 feet (210 meters) thick and consist dominantly of sandstone with lesser amounts of siltstone, shale, dolomitic limestone, and dolomite. An incomplete record containing approximately 100-150 feet (30-46 meters) of Ordovician strata also is present in some of the drill holes. These rocks dominantly consist of cherty dolomite with some intercalated shale and limestone. In addition, most of the area is mantled with a variable thickness of Pleistocene glacial material.

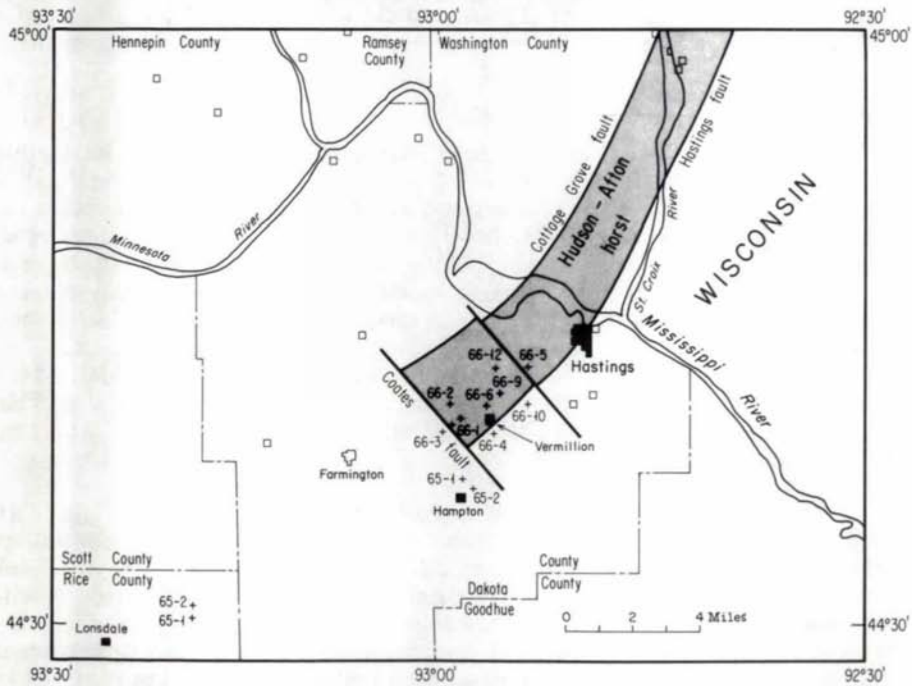


Figure 2 — Pre-Paleozoic geologic map of the southern part of the Hudson-Afton horst showing the location of diamond drill cores evaluated in the study of the Solor Church Formation (+) and other drill holes penetrating Keweenawan strata (▫). The drill hole designations refer to detailed lithic descriptions summarized in Appendix B.

Hinckley Sandstone

The Hinckley Sandstone was first recognized by Winchell in 1884, but he did not formally name and describe it until 1886 (p. 337). The original type section at Hinckley is no longer exposed, but the formation crops out at a number of localities, the largest of which occurs almost continuously for nearly 20 miles (32 km) along the Kettle River north and east of Hinckley (fig. 1). In these outcrops the sandstone is medium- to very thick-bedded, fine- to coarse-grained, and pale red to light pinkish- or brownish-gray in color. Large-scale cross-bedding is common, and current ripple marks are present. Tryhorn and Ojakangas (1972) report that the average framework composition of the Hinckley Sandstone in its type area is about 96 percent quartz, 2 percent feldspar, and 2 percent felsic volcanic rock fragments, metamorphic rock fragments and chert. A similar sandstone has been traced southward in the subsurface to the Minneapolis-St. Paul (Twin Cities) area by Crowley and Thiel (1940), but it has been found only locally south of there. Although the data are sparse, it appears that the Hinckley Sandstone is more than 500 feet (150 meters) thick west of the Douglas fault in east-central Minnesota; however, it thins progressively southward from the type locality until it averages only about 150 feet (46 meters) near the Twin Cities (Grout and others, 1951, p. 1061). South of the Twin Cities, it generally is less than 50 feet (15 meters) thick and in many wells is missing entirely. How much of this thinning results from the original depositional pattern and how much is due to post-Keweenawan, pre-Upper Cambrian erosion is not known.

Recognition of the Hinckley's subsurface distribution is further complicated by a gradational contact between it and the underlying Fond du Lac Formation. Almost everywhere in the subsurface where this contact has been intersected, the pale-red to brownish-gray color of the Hinckley grades downward into the darker red colors of the underlying Fond du Lac Formation without any very great or sudden change. Consequently color is not a consistently useful criterion in distinguishing the two formations. However, the Hinckley Sandstone contains an order of magnitude less feldspar than does the Fond du Lac Formation (Crowley and Thiel, 1940). Therefore the base of the Hinckley Sandstone is arbitrarily placed without regard to color where the feldspar content increases from around 5 percent to more than 10 percent.

The Hinckley Sandstone also closely resembles the overlying Mt. Simon Sandstone of Late Cambrian age. Both formations consist of quartzose sandstone, and thus it is difficult, particularly where only well cuttings are available, to place the Keweenawan-Cambrian boundary with any degree of consistency. Fortunately for this study, however, there are several additional criteria which serve to distinguish the two formations in diamond drill core. Included among these criteria are: (1) the presence of red and green laminated mudstone and shale beds and small-scale planar cross-bedding in the Mt. Simon Sandstone; (2) the presence of abundant quartz overgrowths in the Hinckley Sandstone that results in a generally well indurated rock in contrast to the poorly indurated Mt. Simon Sandstone; (3) the presence of kaolinite and lesser amounts of illite in the clay-size fraction of the Hinckley Sandstone, whereas illite and montmorillonite dominate the clay-size fraction in the basal part of the Mt. Simon Sandstone.

Where it occurs on top of the St. Croix horst, the Hinckley Sandstone is generally less than 50 feet (15 meters) thick and its bottom is sharply defined, at least locally, by as much as 10 feet (3 meters) of conglomeratic sandstone. The conglomeratic clasts generally are pebble size or smaller and consist of detritus derived from the underlying Solor Church Formation. In places, however, clasts of volcanic rocks and quartzite have been recognized.

The Hinckley Sandstone in the subsurface of southeastern Minnesota is similar to that exposed in east-central Minnesota in that it consists dominantly of thin- to thick-bedded, vaguely cross-stratified, medium- to coarse-grained sandstone. A few beds contain scattered granule- or small pebble-size grains which in places define thin laminae. Regardless of grain size, individual grains are moderately to well rounded, and sorting varies from moderate to good (fig. 3). A majority of beds have less than 5 percent clayey matrix, but a few beds contain as much as 10 percent clay which is concentrated in pods and laminae.

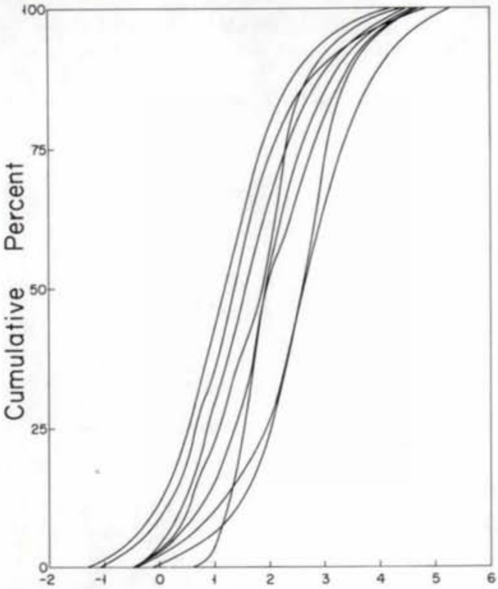
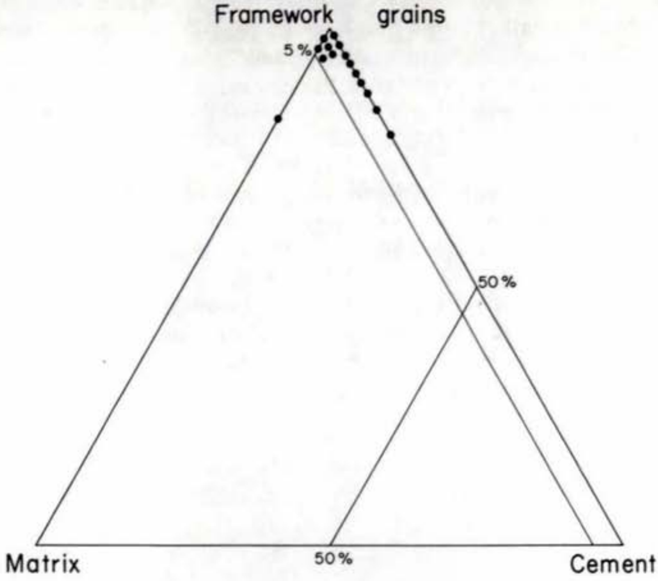


Figure 3 — Grain-size cumulative curves for selected samples of Hinckley Sandstone.

The Hinckley Sandstone as reflected from the study of 17 thin sections -- mostly from subsurface occurrences -- is mineralogically mature (fig 4). Quartz is by far the most abundant mineral. Clear monocrystalline quartz predominates and the majority of grains have strong undulatory extinction. Polycrystalline quartz grains are present in most thin sections, commonly comprising from 5 to 10 percent of the total quartz content. Feldspar generally constitutes less than 5 percent of the framework constituents, although one sample contained 10 percent. Nearly all the feldspar grains are altered, many of them so extensively that their original character is nearly obscured. Microcline, orthoclase, and albite have been recognized. Microcline appears to be most abundant and is less altered than orthoclase.



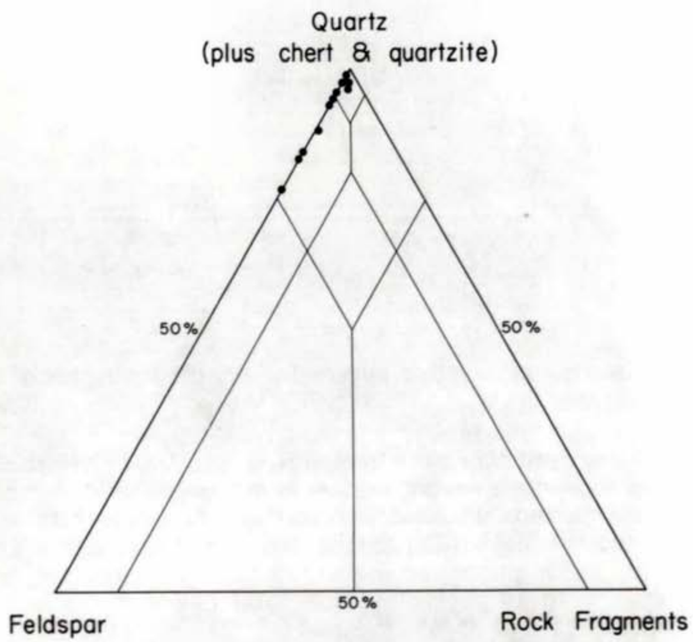


Figure 4 — Textural and compositional characteristics of selected samples of the Hinckley Sandstone. a) texture; b) mineralogy.

Albite grains, identified by polysynthetic twinning, are relatively rare and most commonly are found in rare clay-rich layers. Sand-size rock fragments include trace amounts of quartzite or chert, Solor Church sandstone, and volcanic rocks in basal beds on top of the horst.

Silica cement in the form of detrital grain-overgrowths occurs in all the samples studied. The overgrowths are clear and can be distinguished from the detrital cores only by the presence of vacuoles or dust concentrated along grain-overgrowth boundaries. Various iron-bearing minerals also are present locally as a cementing agent. In outcrop, hematite and/or limonite fills scattered pore spaces, whereas an iron-rich carbonate fills similar pore spaces in subsurface samples. Most likely the oxides resulted from the weathering of this carbonate. The red-colored basal beds of the Hinckley Sandstone also contain a somewhat oxidized iron-bearing carbonate, but because the degree of oxidation decreases upward, it is inferred that this oxidation is related to diagenetic processes that occurred in these strata sometime after deposition.

The clay matrix consists of kaolinite and lesser amounts of admixed illite. Most of the clay is extremely finely divided, but diagenetic crystallization has produced some fairly large flakelets. Some of the clay, particularly in the fine-grained sandstone beds, appears to be of primary origin, but a few clay aggregates may be completely altered feldspar grains. Some mixed-layer illite/montmorillonite was incorporated into the lower few feet of the formation where it overlies weathered Solor Church Formation.

Fond du Lac Formation

The term "Fond du Lac" was applied by Upham (1884) to approximately 300 feet (90 meters) of dark-red to pink shale and red to brown argillaceous to arkosic sandstone that crops out along the St. Louis River west of Duluth (fig. 1). N. H. Winchell (1899, p. 567) denoted these exposures the type section, and Thwaites (1912, p. 69) later described them in some detail. Water ponded by a dam now covers most of the exposures that Thwaites described, and therefore Morey (1967) redescribed the type section as it is now exposed.

Strata lithologically similar to surface exposures of the Fond du Lac Formation were penetrated in the Waseca area where they are disconformably overlain by the Mt. Simon Sandstone. Seismic evidence (Mooney and others, 1970b) indicates that the Fond du Lac Formation is a widespread unit particularly in the basin along the west side of the St. Croix horst. The base of the formation has not been observed anywhere in southeastern Minnesota, but some evidence from the Solor Church Formation suggests that, at least locally, the two formations may be separated by an unconformity.

Cores from four wells in the Waseca area (see Appendix A), comprising about 1,000 feet (305 meters) of strata, were examined and sampled but not logged in detail because of generally poor core recovery. In these wells, the Fond du Lac Formation consists of moderately well cemented sandstone and subordinate amounts of interbedded shale. The sandstone beds appear to be lenticular in shape and range in apparent thickness from less than one to more than 15 feet (4.6 meters). Internally, most beds are either structureless or cross-stratified. Contorted bedding and microfaults indicative of penecontemporaneous deformation also are present locally. The sandstone typically shows a wide range of reddish hues from light red (5R6/6) to dark reddish brown (10R3/4). The associated shales generally are much redder, ranging from moderate (5R4/6) to very dusky red (10R4/6). Mottling is present in both the sandstone and shale with shades and hues of green and yellowish brown particularly common.

The sandstones are very poorly sorted with grain sizes ranging from very fine to coarse sand; silt- and clay-size material is randomly admixed in minor to abundant amounts. Conglomeratic units are fairly common with granule- to pebble-size clasts of fresh and weathered basalt, basalt porphyry, quartz, chert, and lithic sandstone and/or siltstone derived from the Solor Church Formation. In addition, many sandstone beds contain shale chips of obviously intraformational origin.

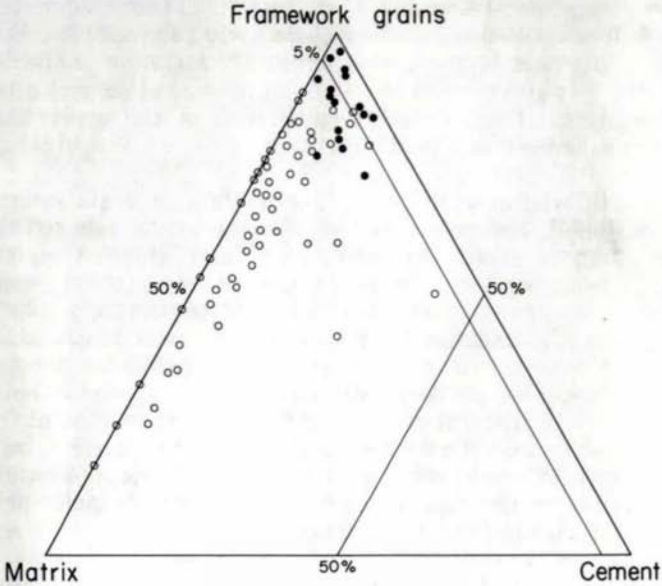
The mineralogy of the sand-size grains resembles, both in quantity and composition, that observed at the type locality of the Fond du Lac Formation (Morey, 1967). Figure 5 is a compositional diagram showing the relative distribution of sand-size components from both localities. Quartz and feldspar are the dominant framework minerals. Orthoclase and microcline are the most abundant feldspars, although twinned and untwinned albite and oligoclase also are present. Sand-size grains of chert and quartzite are the most abundant rock fragments, although granite, schist, and iron-formation clasts are common constituents in most of the samples examined. The clay-size fraction is predominantly illite and chlorite, with lesser amounts of kaolinite and mixed-layer montmorillonite-illite.

Solor Church Formation

A great proportion of the strata previously assigned to the "Red Clastic Series" in southeastern Minnesota is unlike either the Fond du Lac or Hinckley formations described above. For this reason, these strata are assigned to a new lithostratigraphic unit, here named the Solor Church Formation. The name "Solor Church" is taken from a country church in Webster Township (T. 112 N., R. 21 W.), Rice County, located 3 miles (4.8 km) northwest of the type well (refer to the U.S. Geological Survey, Prior Lake 15' quadrangle N4430 - W9315/15, 1957).

Approximately 3,000 feet (910 meters) of diamond drill core from ten separate wells was used to define the Solor Church Formation (see Appendices). Core material from three wells — Lonsdale 65-1, Hampton 65-1, and Vermillion 66-1 — was examined in greatest detail. Of these, Lonsdale 65-1 contains the most complete record, penetrating 1,900 feet (579 meters) of Solor Church Formation with an average core recovery of 99 percent. Because this drill core (located in the SW 1/4, SW 1/4, Sec. 14, T. 112 N., R. 21 W.) is the most complete stratigraphic section available, it is defined here as the type locality. The wells at Hampton 65-1 and Vermillion 66-1 are here defined as secondary reference wells.

The 1,900 feet (579 meters) of strata penetrated at Lonsdale represents only part of the total thickness of the Solor Church Formation.



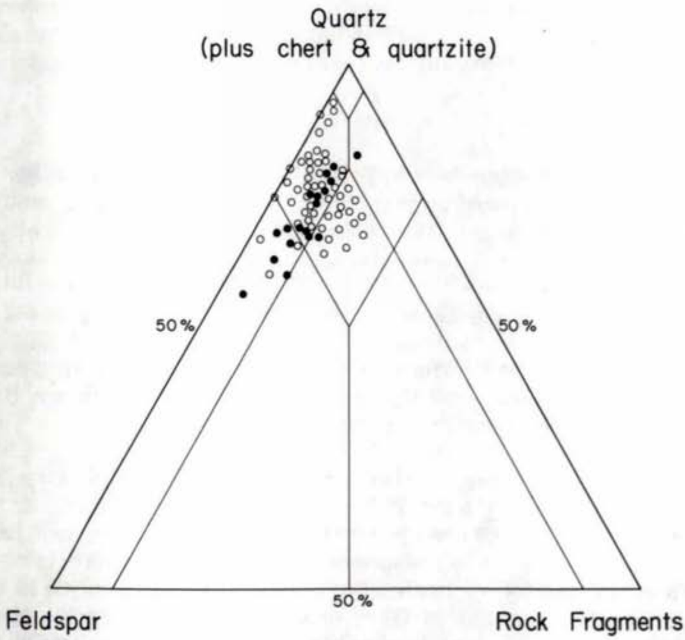


Figure 5 — Textural and compositional characteristics of selected samples of the Fond du Lac Formation (closed circles, type locality at Fond du Lac after Morey, 1967; open circles, selected samples from Waseca area). a) texture; b) mineralogy.

Seismic geophysical evidence (Mooney and others, 1970b) indicates that the Solor Church Formation at Lonsdale is at least 3,200 feet (980 meters) thick. Similarly, a well developed regolith approximately 100 feet (31 meters) thick occurs in the upper part of the formation at Lonsdale. A similar, although thinner regolith was also penetrated at Hampton and at several other widely scattered localities. Thus, an unknown amount of the upper part of the formation may have been removed by erosion.

The regolith, wherever penetrated, is overlain by strata assigned to the Hinckley Sandstone. The upper part of the regolith is typified by a clay, which when damp is plastic in consistency, and which when thoroughly wetted easily disaggregates. In the Lonsdale area, there is a gradual transition, over a stratigraphic interval of approximately 100 feet (31 meters), from clayey material to well indurated rock (fig. 6). Although weathering extends to as much as 100 feet (31 meters) below the base of the Hinckley Sandstone, most of the mineralogic changes appear to occur within the upper 50 feet (15 meters) of the section. The clay-mineral fraction of unweathered Solor Church Formation consists of illite, chlorite, mixed-layer illite/montmorillonite, and trace amounts of kaolinite. Weathering has resulted in several mineralogic changes in the regolith including: (1) the destruction of chlorite in the upper part of the regolith except in a few beds which are still well indurated; (2) an increase, generally upward, in the relative proportion of illite and mixed-layer illite/montmorillonite; (3) the dominance of kaolinite over illite and mixed-layer illite/montmorillonite in the uppermost several feet of the regolith; and (4) a general increase in the structural ordering of illite as evidenced by an increase in the sharpness ratio of the 001 peak on X-ray diffractograms.

Sedimentologic Framework

In general, the Solor Church Formation consists of a rather monotonous sequence of interbedded sandstone, siltstone, and shale or mudstone of alluvial origin. However, a few thin beds of limestone locally occur, especially in what is inferred to be the upper part of the formation. Abrupt alternations in rock type are common, with individual beds generally being less than 10 feet (3 meters) thick; a few sandstone beds, however, are as much as 30 feet thick (9 meters). Because most beds are thin, all the detailed interrelationships of these rocks cannot be graphically portrayed. However, a semi-detailed description of the wells containing the Solor Church Formation is provided in Appendix B.

It is apparent from the descriptions in Appendix B that alternation or cycles of coarse and fine groups of beds is the most prominent sedimentologic feature of the Solor Church Formation. Similar alternations have been described by Allen (1964, 1965), who has referred to them as "fining-upward cycles." Each fining-upward cycle consists of a sequence of beds in which the grain size generally becomes finer upward; thus each cycle generally is divisible into a lower coarse-grained facies and an upper fine-grained facies. In addition, each cycle contains a vertical succession of primary structures and textures indicative of alluvial sedimentation (fig. 7). However, because a second kind of cyclic repetition that also involves the fining-upward of detritus is present in the Solor Church Formation, alternations similar to the "fining-upward cycles" of Allen will be referred to here as "minor cycles" to emphasize their limited stratigraphic extent.

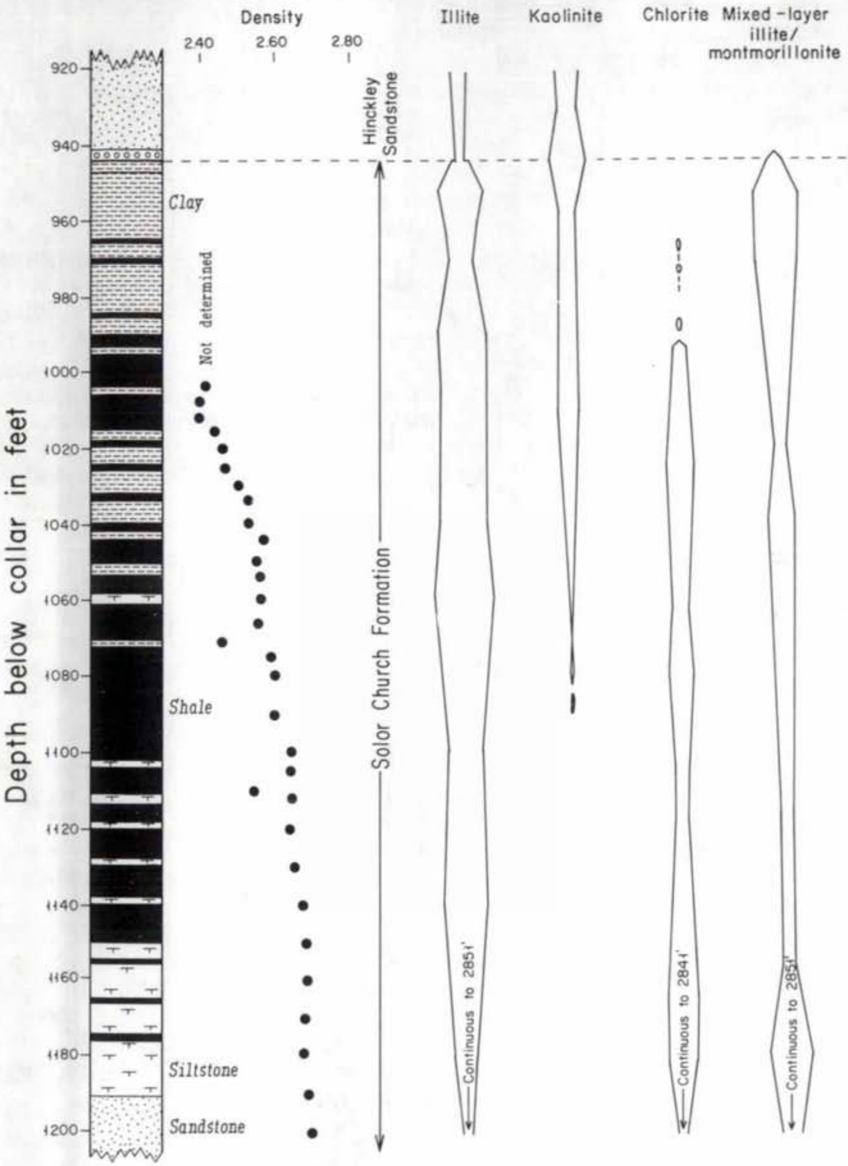


Figure 6 — Generalized stratigraphy and clay mineral distribution in the regolith at the top of the Solor Church Formation in drill hole Lonsdale 65-1. Density determinations by R.J. Ikola.

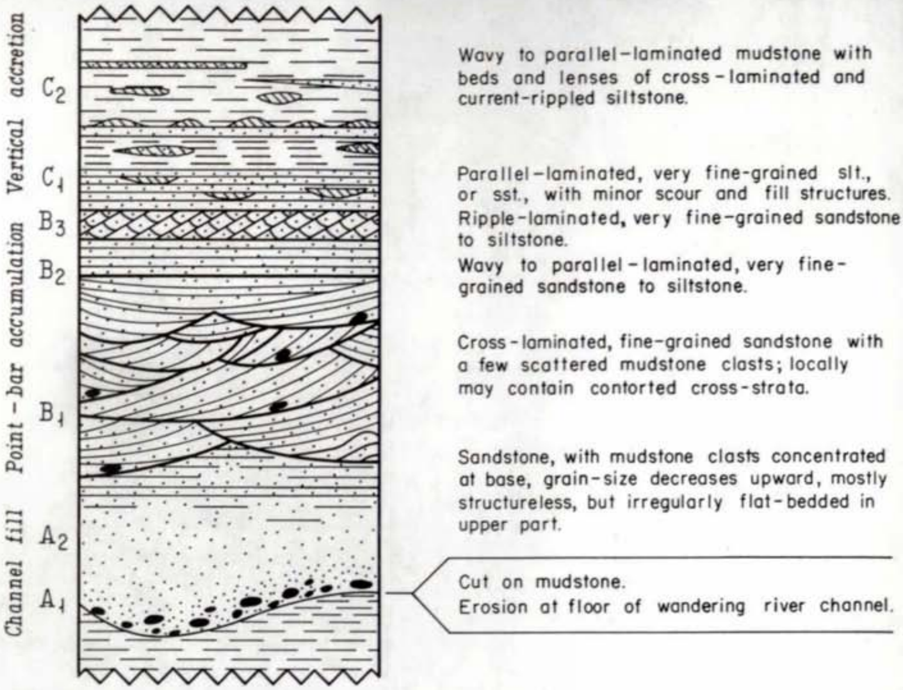


Figure 7 -- Idealized minor cycle or "fining-upward" cycle in the Solor Church Formation and the inferred interpretation of various sedimentary structures.

The term "major cycle" is used here to define subtle, but nevertheless significant, repetition of rock types over stratigraphic thicknesses of as much as 600 feet (180 meters). Each major cycle is characterized by a systematic increase stratigraphically upward, in the amount of mudstone relative to siltstone and sandstone, and each is terminated by an abrupt decrease, over a short vertical distance, in the proportion of mudstone. This fining-upward trend reflects a more or less systematic increase in the thickness of the fine-grained facies, whereas the thickness of the coarse-grained facies in each minor cycle remains relatively constant. As the proportion of siltstone and mudstone increases, there is a corresponding decrease in the apparent grain size of the sand- and silt-size detritus. It is inferred that the major cycles record periods of tectonic instability during the evolution of the St. Croix horst (Morey, 1974).

Petrography

Color: Like many other redbed sequences (Van Houten, 1973), clay- and silt-size beds in the Solor Church Formation contain more iron and thus are more intensely stained by iron-oxides (hematite?) than are the intercalated coarser grained strata. Beds of sandstone and conglomerate generally are moderate red (5R4/6) or pale reddish brown (10R5/4) in color, whereas beds of shale, siltstone and mudstone typically are dusky red (5R3/4) or dark reddish brown (10R3/4) in color. However, the entire Solor Church Formation is not characterized by a red color; there is a gradual downward decrease in the proportion of red-pigmented material leading ultimately to rocks, as at the bottom of Lonsdale 65-1, that are dark greenish gray (5GY4/1 to 5G4/1) to light greenish gray (5GY8/1) in color. The change in color more or less follows a stratigraphically downward trend toward more sandstone. Because there is no apparent change in any of the other sedimentary attributes such as grain size or porosity, it seems likely that oxidizing conditions became dominant after deposition of the Solor Church Formation had started.

Numerous gray-green spots and zones, ranging in size from microscopic specks to parts of beds or entire beds as much as 3 feet (1 meter) thick, are abundant in the generally red strata. More gray-green areas occur near the top of the formation, and there are more gray-green reduction zones in sandstone than in mudstone; this suggests that at least part of the green color resulted from near-surface reducing conditions through groundwater movements (Krumbein and Garrels, 1952). This conclusion is further substantiated in Hampton 65-1 where intervals of gray and greenish-gray strata alternate with intervals of red and reddish-brown strata. In this section there is no apparent correlation between color and depth, or color and rock type. However, a positive correlation does exist between the presence of fractures and the lack of red pigment, suggesting that the fractures served as channelways for migrating oxidizing solutions.

Texture: The Solor Church Formation is composed of dense, well indurated rocks, and therefore it is not possible to completely evaluate many of the textural parameters associated with disaggregated grains. However, an examination of the grain size, rounding, and sphericity of the framework detritus in both the cores and selected thin sections shows that the rocks are texturally immature; all the samples examined in thin section contain more than 5 percent matrix material (fig. 8a).

Although the framework grains exhibit a wide size range, grains of silt to medium-grained sand are most abundant. Sorting is generally poor to moderate and individual grains generally are angular to subrounded. In order to evaluate the size, sorting, and shape of the framework grains, several hundred grains in each of approximately 100 thin sections were examined. Results are graphically summarized in Appendix B. Most of the Solor Church detritus cannot be characterized simply as "medium grained" or "fine grained." Generally, most beds display a markedly bimodal size distribution in which grains the size of either fine sand or medium sand are admixed in a matrix consisting of fine sand-, silt-, or clay-size material. Therefore, sorting within samples the size of a hand specimen is poor. However, samples of about the size of a thin section may appear to be well sorted, for there is little variation in the size of grains within a particular grain-size class.

Marked variation in apparent grain shape also characterizes these rocks. In general, sandstone having a bimodal size distribution also exhibits a bimodal shape distribution. Commonly the larger sand-size grains are moderately well rounded, whereas the smaller grains are angular to poorly rounded.

Mineralogy: Although clastic rocks — sandstone, siltstone, and shale or mudstone — comprise the bulk of the Solor Church Formation, rocks containing more than 50 percent carbonate minerals are present, particularly in what is inferred to be the upper part of the formation. Some of

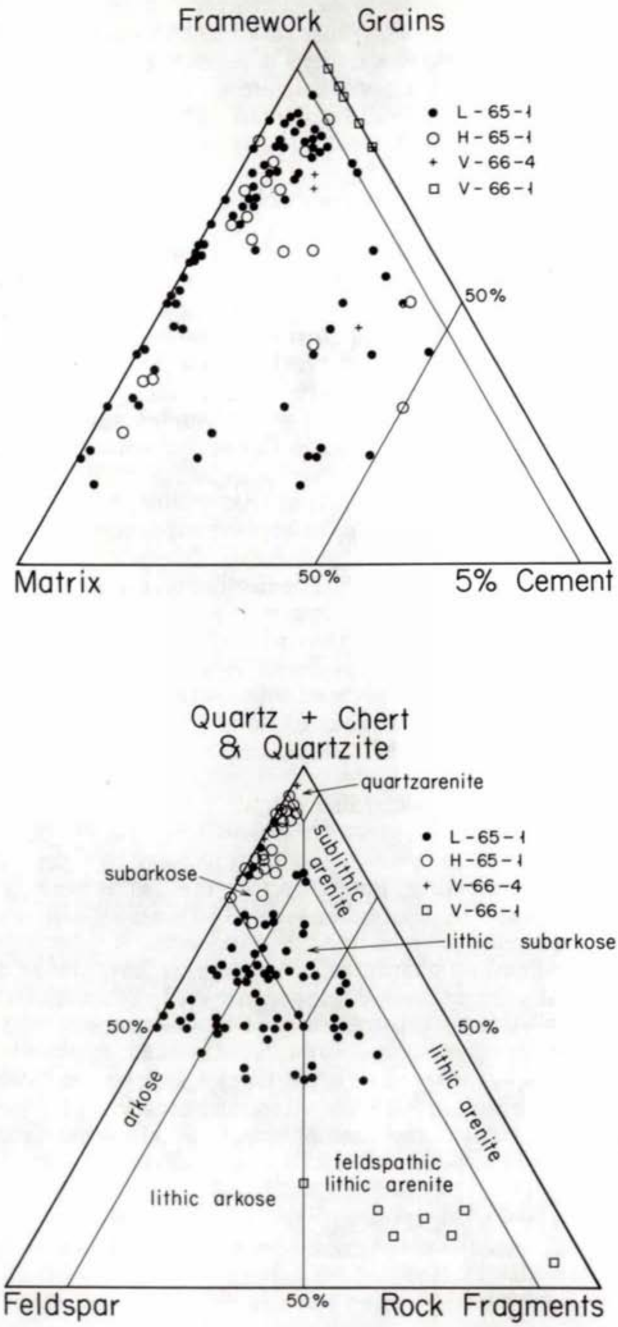


Figure 8 -- Textural and compositional characteristics of selected samples of the Solor Church Formation. a) texture; b) composition.

the carbonate-rich rocks contain a large terrigenous fraction, and as such, are a continuation of calcite-cemented clastic rocks. Other carbonate-rich rocks have a low proportion of terrigenous material and are characterized by typical limestone textures.

Sandstone and siltstone of the Solor Church Formation are mineralogically immature in that they contain appreciable amounts of feldspar and aphanitic igneous rock fragments (Morey, 1972). Of the thin sections examined in detail, approximately 2 percent are quartzarenite, 31 percent subarkose, 20 percent arkose, 22 percent lithic arkose, 14 percent feldspathic lithic arenite, 10 percent lithic subarkose, and 1 percent lithic arenite (fig. 8b). Part of the mineralogic variation results from differences in grain size; very fine-grained sandstone and siltstone contain more quartz and less feldspar and rock fragments than do their coarser grained counterparts. However, some of the mineralogic variations appear to be stratigraphically controlled in that there is a crude trend toward less labile constituents in the upper parts of the formation. For example, quartz averages 84 percent at Hampton, 57 percent at Lonsdale, and 13 percent in Vermillion 66-1. In contrast, feldspar decreases in abundance stratigraphically upward, averaging 30 percent in Vermillion 66-1 and 15 percent at Hampton. Similarly, sand-size aphanitic rock fragments, consisting of lath-shaped plagioclase crystals set in a fine-grained, nearly opaque groundmass, are almost lacking at Hampton, but constitute a large proportion of the basal rocks in Vermillion 66-1.

Siltstone in the Solor Church Formation is the fine-grained equivalent of the sandstone, and there is more or less continuous gradation between the two rock types. Most of the siltstone is poorly sorted. Silt and very fine sand-size grains of quartz, feldspar, and rock fragments comprise about 30 to 60 percent of the rock. The remainder consists of very finely crystalline clay minerals, chiefly illite or mixed-layer illite/montmorillonite, together with particles and irregular patches of iron oxides and calcite.

Mudstone in the Solor Church Formation has either a laminated or massive fabric. Many mudstone units are fissile and therefore can properly be called shales. The presence or absence of parting planes is a function of the amount and distribution of the silt-size fraction; fissile and laminated rocks contain small amounts of silt, concentrated in discontinuous layers less than a millimeter thick. Structureless beds, however, are very silty and the silt-size detritus generally is randomly distributed; these rocks commonly break with a flat-conchoidal fracture. X-ray diffraction studies show that the clay-size fraction is predominantly mixed-layer illite/montmorillonite, with lesser amounts of illite and chlorite. Hematite is a common constituent, imparting a red color to many beds, and calcite is locally very abundant.

Conglomeratic units are fairly common throughout the formation. All are intraformational in origin, except near the base of the formation in Vermillion 66-1 where pebble- and cobble-size clasts of basalt are present. The intraformational conglomerates consist of angular to subangular pebble-size clasts of shale, mudstone, and siltstone set in a sand-size matrix. Generally, intraformational conglomerates occur in the basal parts of thick sandstone beds, which are separated from underlying argillaceous rocks by scoured surfaces; it is inferred that these argillaceous rocks are the source of the conglomeratic clasts.

Carbonate Rocks

Two types of carbonate-rich rocks occur in the Solor Church Formation. Rocks of the first type typically are clastic rocks that contain as much as 60 percent calcite. This rock type occurs more or less randomly throughout the formation and has no apparent relationship to stratigraphic position. In contrast, the carbonate rocks of the second type are true limestones. These limestones have a restricted stratigraphic distribution and occur only where mudstone and/or shale units are abundant.

Two texturally distinct kinds of limestone are recognized. The first consists of either oolites or intraclasts cemented by clear, sparry calcite. The oolites are fairly well rounded and average 0.60 mm in diameter (range 0.3 to 1.0 mm). Many smaller oolites have a simple structure consisting of a nucleus — either quartz or chamosite — surrounded by concentric rings of iron-oxide-stained calcium carbonate. Some of the larger oolites also are of this type, but more commonly they consist of several simple oolites which are linked together and surrounded by a new set of concentric rings. In contrast, the intraclasts are "roller-like" in shape. They average 2.4 mm long and 0.8 mm wide, and are oriented more or less parallel to each other so as to define a crude layering. The intraclasts consist of microcrystalline calcite and some are surrounded by a thin oolitic shell.

The second and less common limestone type consists dominantly of microcrystalline calcite, which is present both as intraclasts and matrix material. The microcrystalline material has been pervasively recrystallized, and commonly it is difficult to distinguish the matrix material from the intraclasts in thin section.

POSSIBLE CORRELATIONS WITH OTHER KEWEENAWAN SEDIMENTARY ROCKS IN MINNESOTA AND THEIR INFERRED DISTRIBUTION

Although detailed data pertaining to the subsurface stratigraphic relations of Upper Keweenawan sedimentary rocks in east-central and southeastern Minnesota are very limited, Kirwin (1963) established that quartz and K-feldspar are only minor constituents near the bottom of the sedimentary pile, and that upward in the section, extrusive volcanic rock debris and plagioclase decrease as the relative abundance of quartz and K-feldspar increases. Consequently, Kirwin (1963, p. 30-32) characterized five lithic units on the basis of these mineralogic changes; their approximate mineral compositions are shown in Figure 9.

A comparison of Figures 4b, 5b, 8b, and 9 shows that the Hinckley Sandstone corresponds to Kirwin's unit 1, and that the sandstone in the Vermillion 66-1 falls well within the compositional range of Kirwin's unit 5. Likewise, the bulk of the Solor Church Formation at Lonsdale appears to be mineralogically equivalent to Kirwin's unit 4. Although it is not possible to separate Kirwin's units 2 and 3 using the mineral end members shown in Figure 9, the Hampton 65-1 and 65-2 sections appear to be equivalent to Kirwin's unit 3 on the basis of abundant plagioclase relative to K-feldspar. Similarly, the Fond du Lac Formation appears to be equivalent to Kirwin's unit 2 on the basis of abundant K-feldspar relative to plagioclase. Thus,

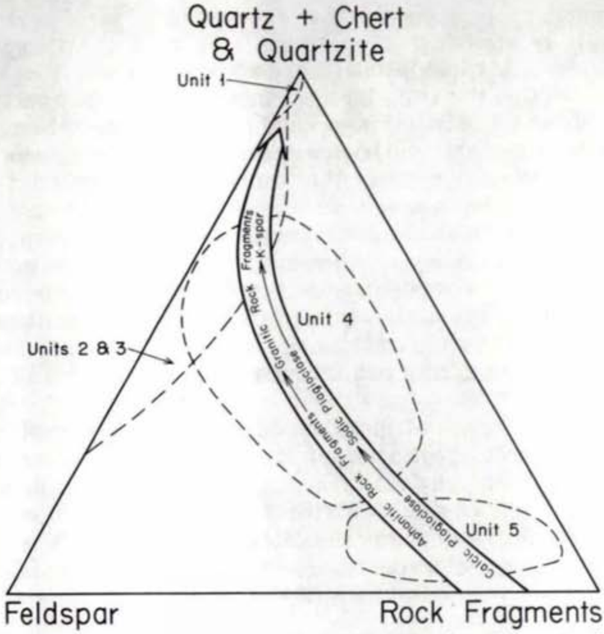


Figure 9 — Triangular diagram showing mineralogic characteristics of units in a complete sequence of Keweenawan sedimentary rocks as recognized by Kirwin (1963).

changes in the mineralogic composition of these rocks appear to be a useful criterion in establishing relative position within the Keweenawan sedimentary sequence.

A generalized stratigraphic section across the St. Croix horst is shown in Figure 10. The structural configuration is based largely on data obtained by geophysical methods (Mooney and others, 1970a), whereas the various lithostratigraphic units are identified on the basis of petrographic criteria outlined by Kirwin (1963) and Morey (1972).

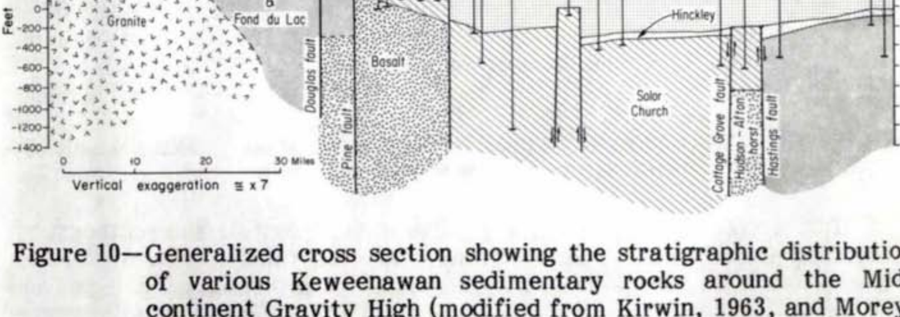


Figure 10—Generalized cross section showing the stratigraphic distribution of various Keweenawan sedimentary rocks around the Midcontinent Gravity High (modified from Kirwin, 1963, and Morey, 1972). The location of the cross section is shown in Figure 1.

It is immediately apparent that the distribution of sedimentary rock types is closely related to the structure. West of the Douglas fault, the contact between the Hinckley Sandstone and the underlying Fond du Lac Formation is difficult to define because of an apparently continuous transition in color and mineral composition. The contact between the Fond du Lac Formation and the underlying Solor Church Formation has not been penetrated by drilling. Because the mineralogy of the upper part of the Solor Church Formation resembles in some ways that of the Fond du Lac Formation, Kirwin (1963) believed that sedimentation was more or less continuous across this boundary. However, the presence of pebbles of Solor Church-like material in the Fond du Lac Formation (Morey, 1972) implies that the Solor Church Formation was lithified prior to deposition of the Fond du Lac Formation. Thus a hiatus of unknown duration is inferred to separate the times of deposition of the two formations.

A depositional break of unknown duration also occurred on top of the St. Croix horst prior to deposition of the Hinckley Sandstone as shown by: (1) the near absence of any identifiable Fond du Lac-like material; and (2) the presence of a thick regolith at the top of the Solor Church Formation where it is overlain by Hinckley Sandstone. This contact is characterized by: (1) an abrupt change in rock type, and (2) the presence of Solor Church regolithic material in the basal beds of the Hinckley Sandstone.

The above relationships strongly imply that the St. Croix horst stood as a positive area during Fond du Lac deposition. However, the apparent distribution and thickness of the Hinckley Sandstone on top of the St. Croix horst may not be related entirely to Keweenawan tectonism inasmuch as several lines of evidence indicate a period of erosion prior to the start of Upper Cambrian sedimentation: (1) The Hinckley Sandstone and the Solor Church regolith are not found on top of the Hudson-Afton horst, a subsidiary block on the St. Croix horst that was uplifted to a greater extent than was the main part of the St. Croix horst. Thus erosion there must have been more extensive than on the St. Croix horst proper. (2) There appears to be an angular unconformity between the Upper Cambrian Mt. Simon Sandstone and the Keweenawan strata on top of the St. Croix horst, as evidenced by the discordant orientation of bedding planes relative to the direction of the core axis, whereas bedding-plane relationships are more or less concordant along the flanks of the horst. (3) The apparent juxtaposition of the Hinckley Sandstone with Middle Keweenawan lava flows along the Douglas fault on the west side of the St. Croix horst implies that some movement occurred during or after deposition of the Hinckley Sandstone. Thus it can be argued that the distribution of the Hinckley Sandstone on the top of the St. Croix horst is related to both pre- and post-Hinckley movements on the principal and subsidiary faults associated with that structure.

AGE AND POSSIBLE CORRELATION WITH OTHER KEWEENAWAN STRATA IN THE LAKE SUPERIOR REGION

The Keweenawan sedimentary rocks in east-central and southeastern Minnesota are inferred to be a continuation of a thick sequence of rocks exposed along the south shore of Lake Superior in northern Michigan and Wisconsin. There, the sequence consists of interbedded conglomerate, sandstone, and shale, and comprises an aggregate thickness of approximately

18,000 feet (5,500 meters) (Thwaites, 1912; Tyler and others, 1940). In Wisconsin the strata are divided into two groups, the Oronto Group and the overlying Bayfield Group. In turn, each group is subdivided into several formations (tbl. 1). Published information regarding the mineralogic composition of these rocks is generally lacking. However, to judge from the available data, rocks of the Oronto Group appear to be better indurated, but less mature, both texturally and mineralogically, than those of the Bayfield Group. In addition, detritus of the Oronto Group consists in large part of felsic and mafic volcanic rock fragments, plagioclase, and quartz (Thwaites, 1912; White and Wright, 1960; Hamblin and Horner, 1961; Ensign and others, 1968; Hubbard, 1972), whereas that of the Bayfield Group is more quartzose and microcline-rich (Thwaites, 1912; Myers, 1971). Thus in a general way the mineralogy of the Solor Church Formation is similar to that of the Oronto Group. However, to judge from the seismic data of Mooney and others (1970a), rocks assigned to the Solor Church Formation on the west side of the St. Croix horst are not continuous with those assigned to the Oronto Group. Rather, the Fond du Lac Formation appears to overlie directly pre-Keweenawan basement rocks south and southwest of Duluth. The lack of additional data precludes any more precise conclusions as to possible correlations.

In contrast, the inferred correlation of the Fond du Lac and Hinckley formations with units in the Bayfield Group has been recognized for more than 30 years. Tyler and others (1940, p. 1470) concluded that the Fond du Lac Formation is correlative with the Orienta Sandstone and that the Hinckley Sandstone is correlative with the Devils Island Sandstone. The Chequamegon Sandstone, or the uppermost unit of the Bayfield Group, apparently was never deposited in Minnesota, for no trace of it has been recognized. Available seismic evidence (Mooney and others, 1970a, b) more or less supports these inferred correlations.

In Michigan, rocks correlative with those in the Oronto Group comprise an integral part of Irving's (1883) Keweenawan; hence they are considered part of what is referred to today as the Keweenawan System (Goldich and others, 1961) or Keweenawan Supergroup (U.S. Geological Survey usage). In early reports on the Lake Superior region, it was assumed that lava flows, associated interflow sedimentary strata and various kinds of mafic intrusions represented a short-lived igneous event which was defined as comprising the middle part of the Keweenawan succession. This igneous event was thought to have been preceded and followed by deposition of dominantly clastic strata. Hence the Keweenawan System was divided into a lower, middle, and upper part. This usage was followed in Minnesota; the lava flows were assigned to the Middle Keweenawan, and the red-colored strata were assigned to the Upper Keweenawan (Grout and others, 1951).

White (1972) has shown that Irving's original Middle-Upper Keweenawan boundary cannot be followed for any distance away from its type locality. Consequently, he suggested that the top of the Copper Harbor Conglomerate comes closer to marking the end of the Keweenawan volcanism than does any other major stratigraphic break. Therefore, he proposed that the base of the Nonesuch Shale be adopted as the base of the Upper Keweenawan. Unfortunately, this boundary cannot be recognized in Minnesota because precise equivalents of the Copper Harbor Conglomerate and Nonesuch Shale cannot be defined using the data now available.

Therefore the older Keweenawan nomenclature is retained, with the recognition that part of the Solor Church Formation may be equivalent to rocks that White would assign to the Middle Keweenawan in Michigan.

The age of the Bayfield Group, and hence the age of the Fond du Lac and Hinckley formations, also is problematical. The Bayfield Group probably is unconformable, at least locally, with older Oronto strata (Ostrom, 1967; Myers, 1971), but Ostrom (1967) suggests that the upper part of the group may be equivalent to the Mt. Simon Sandstone. Consequently, he tentatively assigned the Bayfield Group in Wisconsin to the Cambrian System. In Minnesota the Fond du Lac and Hinckley formations appear to be separated from the underlying Solor Church Formation and Mt. Simon Sandstone by unconformities. Therefore, the Hinckley and Fond du Lac formation rocks are older than definitely Keweenawan strata and younger than definitely Cambrian strata. Inasmuch as the Fond du Lac and Hinckley formations appear to comprise part of what is thought to be a dominantly Keweenawan structural feature (Sims and Morey, 1972), they are assigned Late Keweenawan age in Minnesota.

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Mr. Robert Miller of Northern Natural Gas Company, Omaha, Nebraska, kindly made available geophysical logs, well cuttings, cores, and other material from wells drilled in 1965 and 1966 in the Lonsdale, Hampton, and Vermillion areas. Likewise, the Minneapolis Gas Company made available results of their exploratory drilling in the Waseca area. Permission from these companies to study this material and to publish the results is gratefully acknowledged. A research grant from the Graduate School of the University of Minnesota provided funds for the laboratory phases of this study and is gratefully acknowledged. Richard Darling prepared and drafted the illustrations.

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APPENDIX A

SUMMARY OF LOCATIONS OF DRILL HOLES USED IN THIS REPORT

Well name	Location	Collar elevation (feet)	Total depth (feet)	Depth to top of Precambrian (feet)
	Dakota County			
Vermillion 66-1	85 feet N. of South line, 256 feet West of S.W. cor. E. 1/2, S.E. 1/4, sec. 17, T. 114 N., R. 18 W.	890	1495	908
66-2	90 feet N. of South line, 1 foot + E. of West line, sec. 8, T. 114 N., R. 18 W.	917	1114	920
66-3	1262 feet N. of South line, 92.8 feet W. of E. line, sec. 19, T. 114 N., R. 18 W.	844	967	910
66-4	863 feet W. of S.E. cor., 91 feet N. of South line, S.W. 1/4, sec. 21, T. 114 N., R. 18 W.	852	892	761
66-5	860 feet E. of West line, 17 feet S. of North line, W. 1/2, S.E. 1/4, sec. 36, T. 115 N., R. 18 W.	860.4	957	910
66-6	125.7 feet N. of South line, 176.4 feet W. of East line, S.W. 1/4, sec. 10, T. 114 N., R. 18 W.	824.6	897	846
66-9	78.5 feet E. of West line, 676.5 feet S. of North line, sec. 11, T. 114 N., R. 18 W.	882	946	916
66-10	685.4 feet N. of South line, 67.0 feet E. of West line, S.E. 1/4, sec. 11, T. 114 N., R. 18 W.	820	930	926
Hampton 65-1	1320 feet S., 500 feet E., of N.W. cor., sec. 4, T. 113 N., R. 18 W.	978	1366	916
65-2	2732 feet E. of West line, 82 feet N. of center of sec., N.E. 1/4, sec. 4, T. 113 N., R. 18 W.	947	1045	921
	Rice County			
Lonsdale 65-1	109 feet S., 63.5 feet E. of N.W. cor., S.W. 1/4, S.W. 1/4, sec. 14, T. 112 N., R. 21 W.	1016	2843	945
65-2	66 feet S., 55 feet E. of N.W. cor., sec. 14, T. 112 N., R. 21 W.	1094	1045	1034
	Waseca County			
Fretham 1	S. 1/2, N.E. 1/4, S.W. 1/4, sec. 20, T. 108 N., R. 22 W.	1142	2159	1238
Kanne 1	S.E. 1/4, S.W. 1/4, S.W. 1/4, sec. 4, T. 108 N., R. 22 W.	1119	2274	1122
Melstrom 1	S.W. 1/4, S.E. 1/4, S.W. 1/4, sec. 28, T. 109 N., R. 22 W.	1080	1302	1170
Steinhaus 1	S.W. 1/4, S.E. 1/4, sec. 2, T. 108 N., R. 23 W.	1078	2390	1284

APPENDIX B

DESCRIPTION OF WELLS CONTAINING SOLOR CHURCH FORMATION

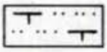
In order to tabulate as much information as possible in a limited amount of space, a graphic means of presentation was used in preparing the figures in this appendix. The key to symbols used is as follows:

Column 1. — Depth in feet relative to the ground elevation at the drill site.

Column 2. — The columnar section is a graphic representation of the lithologies observed. In intervals where alternation of rock types is common, the section is somewhat generalized. However, the generalization does not detract from the sedimentological aspects that can be inferred from the columnar section. Symbols used are:

I. Basic lithologic symbols

 Sandstone

 Siltstone

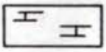
 Mudstone

 Claystone

 Conglomerate

 Breccia, may be either sedimentary or tectonic

II. Modifying lithologic symbols (used in combination with one of those shown above)

 Calcareous

 Shaly lenses, pods, or thin beds

III. Contact between lithologic units

——— sharp or abrupt

- - - - - gradational

Column 3. — The color is that of a dry, freshly split surface as determined by comparison with the Geological Society of America Rock Color Chart (1962 printing).

Column 4. — The depositional features described here are either of a primary depositional or of a soft-sediment post-depositional origin. Post-consolidation shear zones also are shown. The general symbols used are as follows:

1. Bedding structures

—	non-bedded, very thick-bedded, or slightly bedded
=	thick-bedded
≡	thin-bedded
≣	very thin-bedded or laminated
f≡	laminated and fissile
	cross-bedded or cross-laminated
↑	gradation of one type of bedding to another type
	contorted or convoluted bedding

II. Post-depositional structures

	load casts
	flame structures and/or clastic dikes
	overturned or oversteepened foreset cross-laminae
	slump structure
	scour and fill structure; where structure is large, scour and fill structures are graphically shown in columnar section.

III. Post-consolidation structures

	shear zones or intervals containing abundant slickensides

Column 5. — Grain size and sorting were estimated from hand specimens and thin sections by comparison with batches of known grain sizes that were prepared for this purpose based on categories defined by Wentworth. In general, grain size is indicated by the use of circles whose diameters are proportional to the maximum grain size in the rock. Symbols used are as follows:

○	very coarse-grained sand
○	coarse-grained sand
○	medium-grained sand
○	fine-grained sand
●	very fine-grained sand
∘	coarse-grained silt
	fine-grained silt

A combination of two or more symbols indicates a bimodal grain-size distribution of framework grains at a specific depth, whereas a vertical arrow indicates apparent grading or upward fining over an interval of several feet.

Sorting also was estimated visually and ranked into one of four categories:

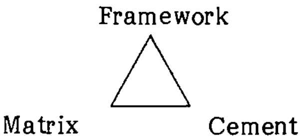
1. very poorly sorted
2. poorly sorted
3. moderately well sorted
4. well sorted

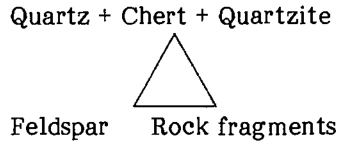
Again, a vertical arrow indicates a more or less gradational change in sorting.

Column 6. — Sphericity and roundness were estimated from hand specimens and thin sections by comparison with charts of Krumbein (1941) and Powers (1953) showing grains of calculated degrees of rounding and sphericity. Degree of sphericity is shown by a numerical value of the ratio of the apparent short dimension to the apparent long dimension. Roundness is indicated by: A, angular; S, subrounded; R, rounded.

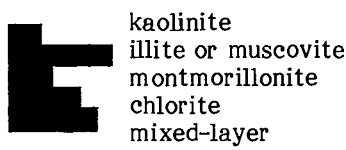
Column 7. — Closed circles indicate samples used for X-ray analysis, open circles indicate a thin section study, and closed squares indicate both X-ray and thin section.

Column 8. — Modal compositions shown in this column were obtained by counting 100 points on each thin section to determine the relative amounts of framework grains, matrix, and cement; additional observations were then made on each thin section until 100 framework grains were classified. These data are presented in two triangular diagrams as follows:





Column 9. — Oriented aggregates of the less-than-2-micron fraction were prepared by the sedimentation of disaggregated material on glass slides. The sedimented material was then dried at room temperature. X-ray diffraction data were obtained first on air-dried slides that were again X-rayed after each slide had been placed in an ethylene-glycol atmosphere for approximately 24 hours to facilitate recognition of the presence of expansible clay minerals. If it was necessary to distinguish chlorite from kaolinite, a second air-dried slide of each sample was heated to 400° C. in a small electric muffle furnace for one hour. Heat treatment removed diffraction peaks from the record for kaolinite and left those for chlorite. Nickel-filtered copper radiation was used throughout the study; machine settings of 40 KV, 20 ma, and a goniometer speed of 2° 2θ/minute were used. Data obtained are presented in a series of bar graphs showing the relative size of the 001 peak for kaolinite, illite or muscovite, montmorillonite, chlorite, and mixed-layer illite/montmorillonite structures based on the total of all peaks present equaling 100%.



Column 10. — The mineralogic nature of the cementing material in these rocks is summarized in this column. In general, the summaries are self-explanatory.

Column 11. — Rock names used in this report were determined from relative proportions of framework constituents and from McBride's (1963) classification of clastic rocks, which has end-members of quartz (including fragments of quartzite and chert), feldspar, and other rock fragments. Although this classification is strictly applicable only to sandstones, the same nomenclature is used here for the siltstones.

Figure B-1 — Lithic log of diamond drill core Lonsdale 65-1

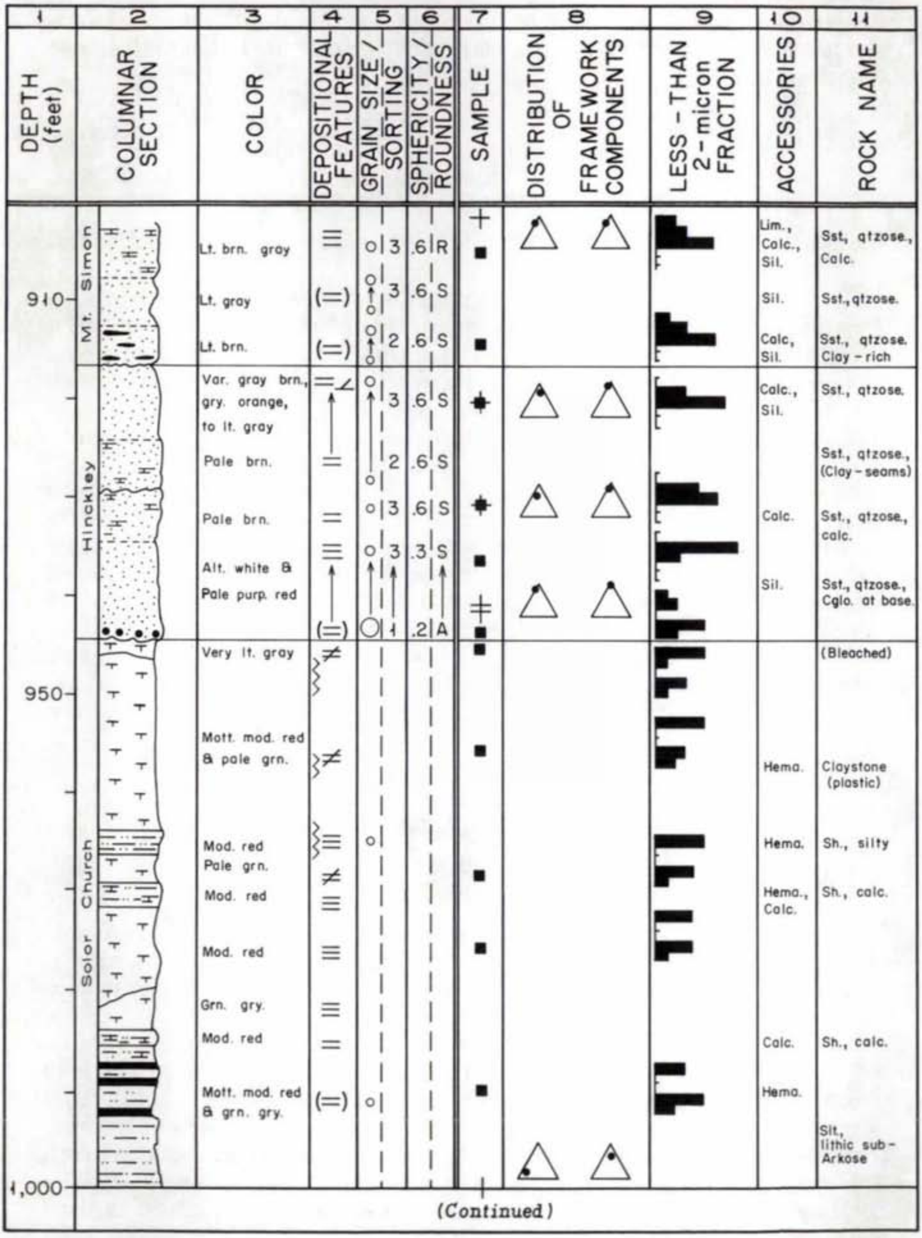


Figure B-1 — Lithic log of diamond drill core Lonsdale 65-1 (cont.)

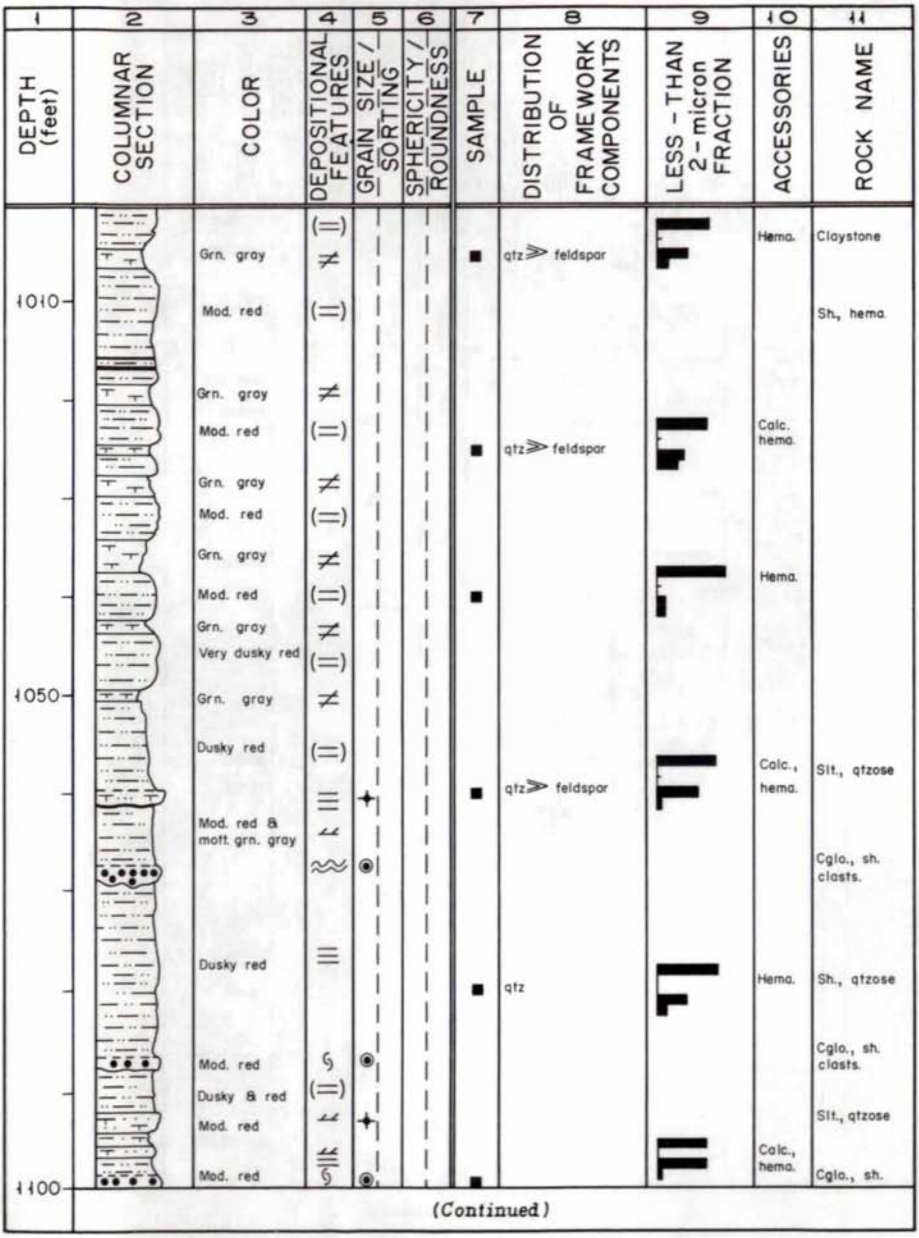
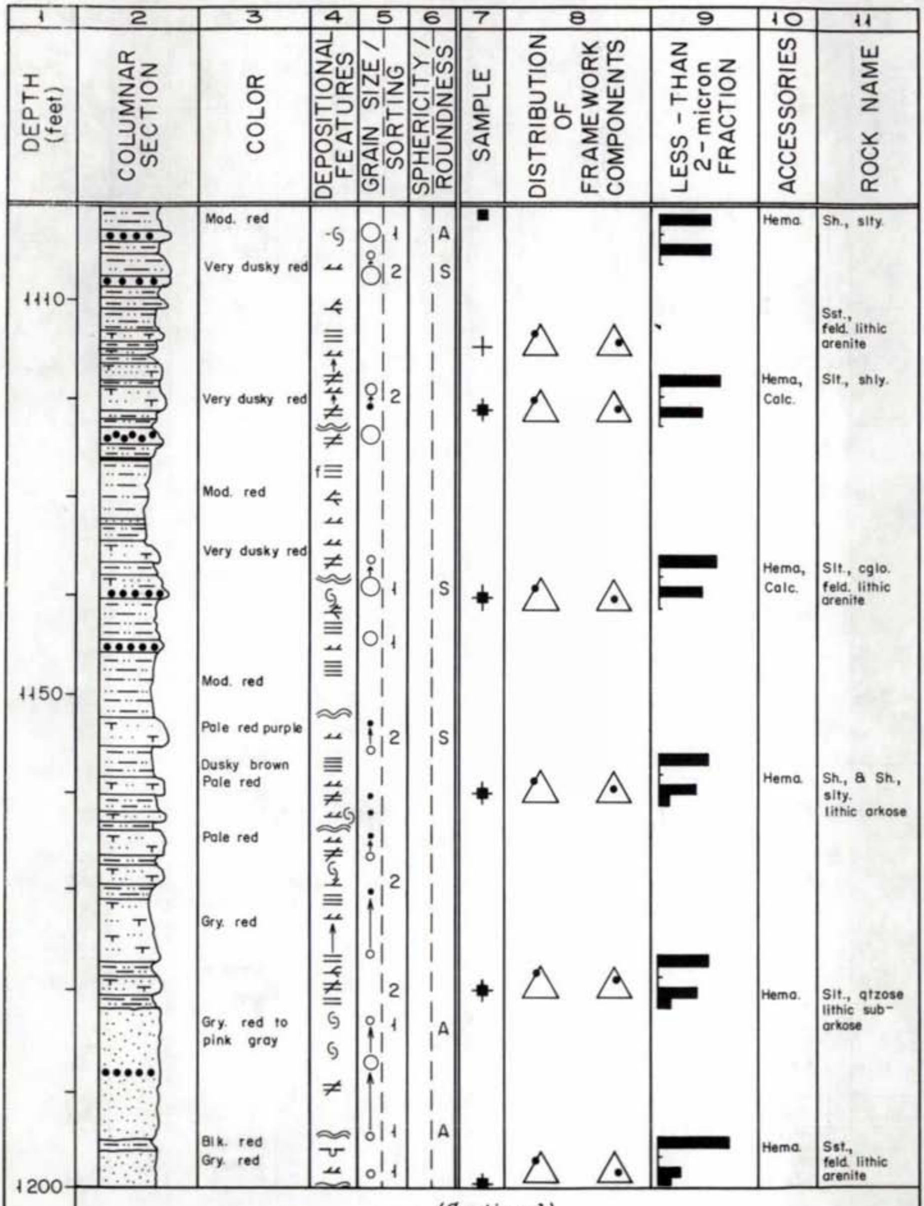


Figure B-1 — Lithic log of diamond drill core Lonsdale 65-1 (cont.)



(Continued)

Figure B-1 -- Lithic log of diamond drill core Lonsdale 65-1 (cont.)

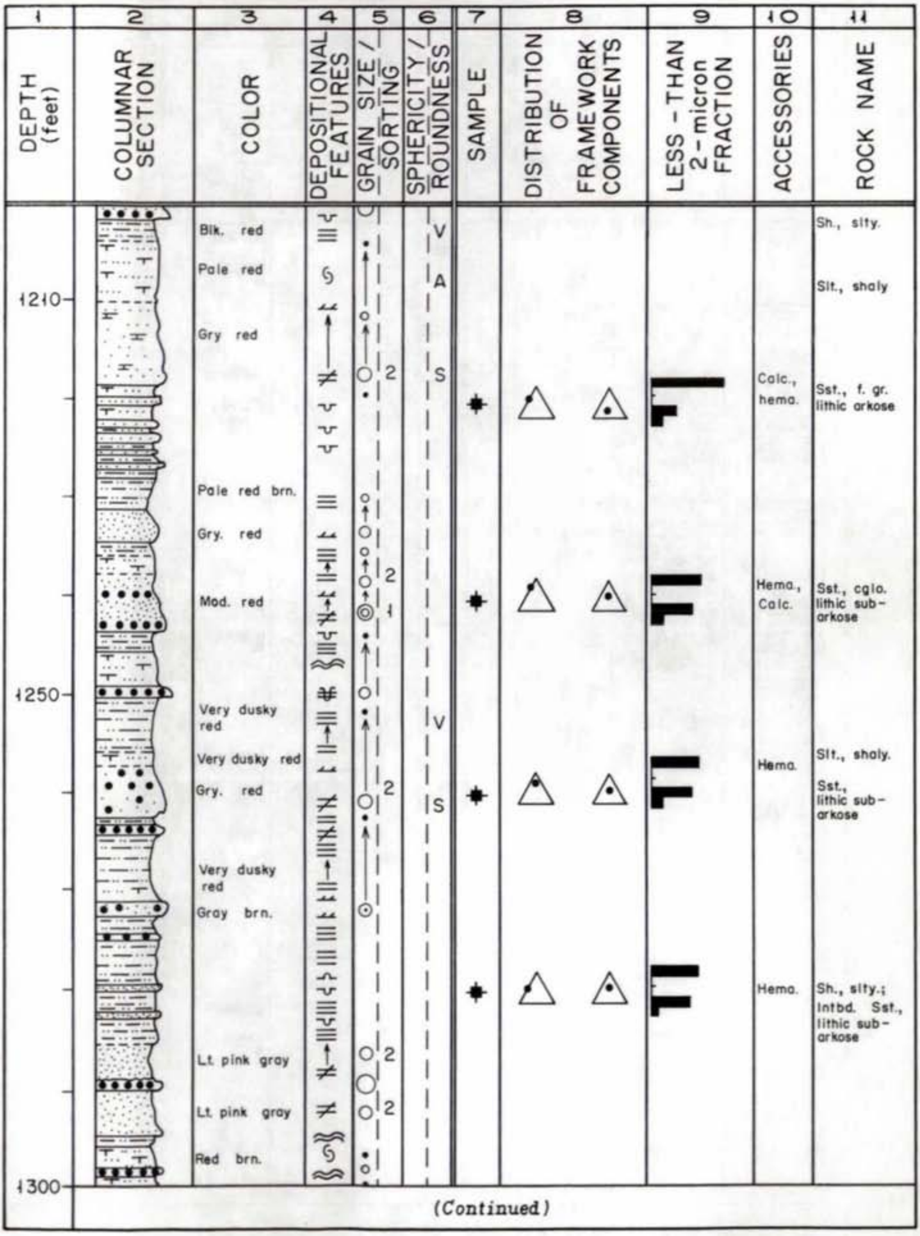


Figure B-1 — Lithic log of diamond drill core Lonsdale 65-1 (cont.)

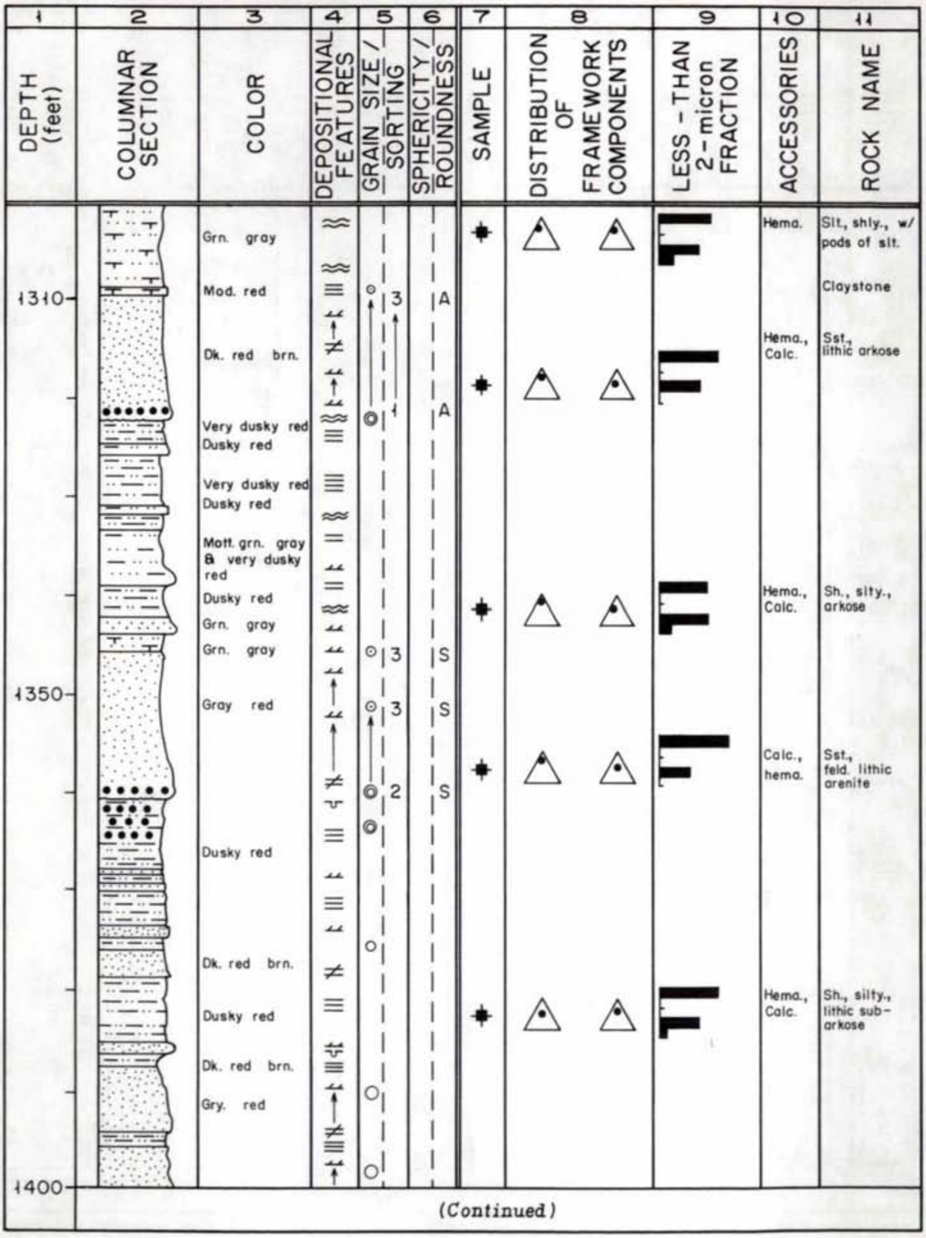


Figure B-1 — Lithic log of diamond drill core Lonsdale 65-1 (cont.)

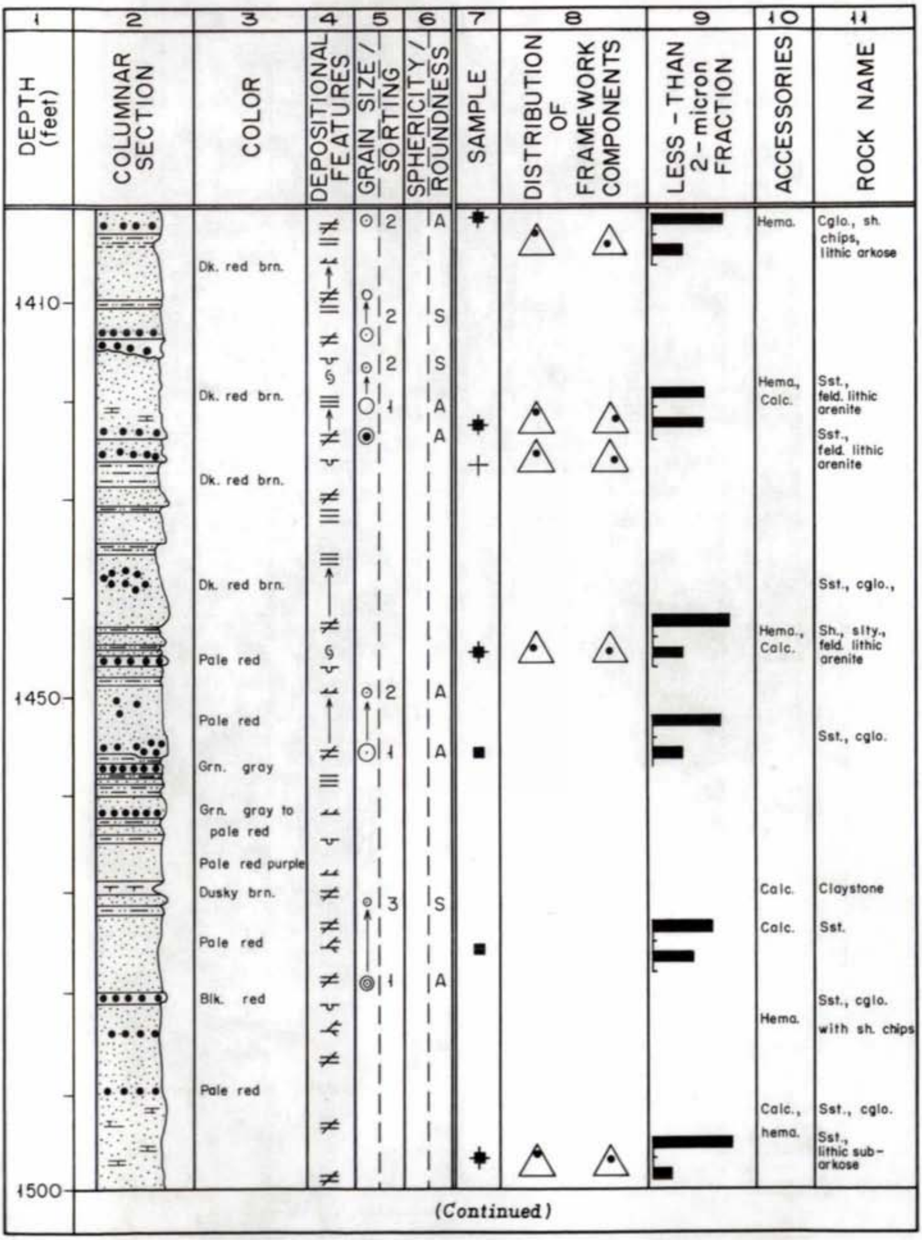


Figure B-1 — Lithic log of diamond drill core Lonsdale 65-1 (cont.)

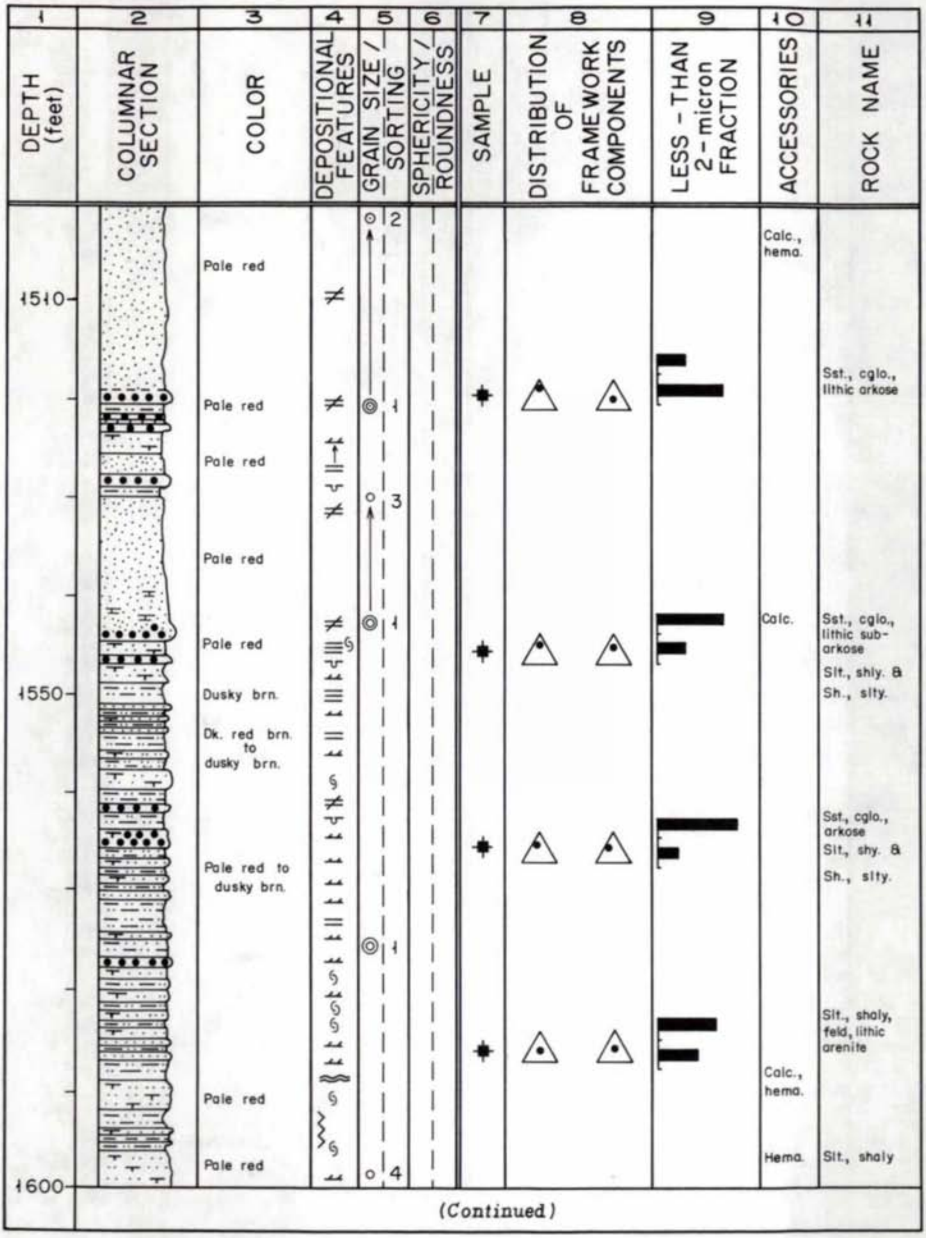


Figure B-1 — Lithic log of diamond drill core Lonsdale 65-1 (cont.)

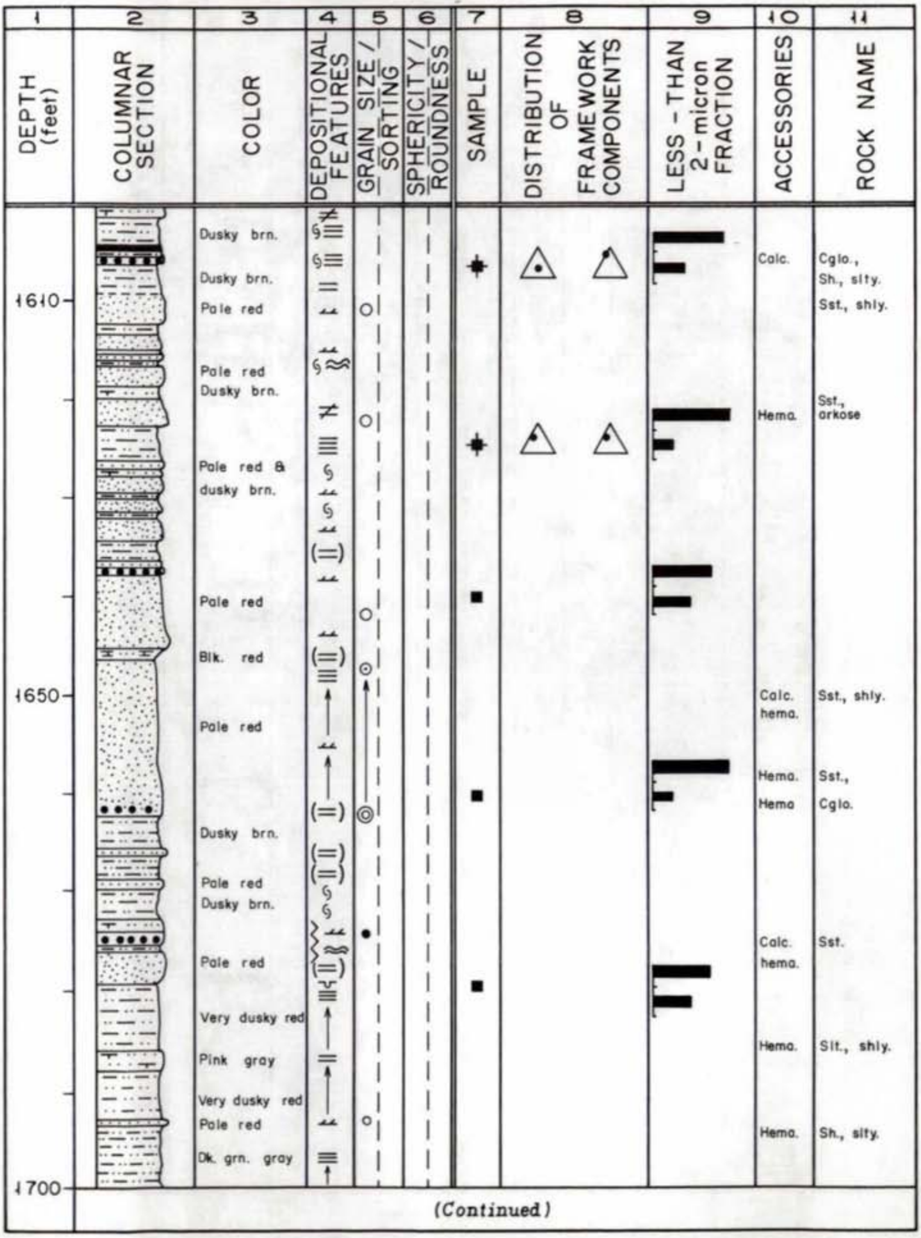


Figure B-1 — Lithic log of diamond drill core Lonsdale 65-1 (cont.)

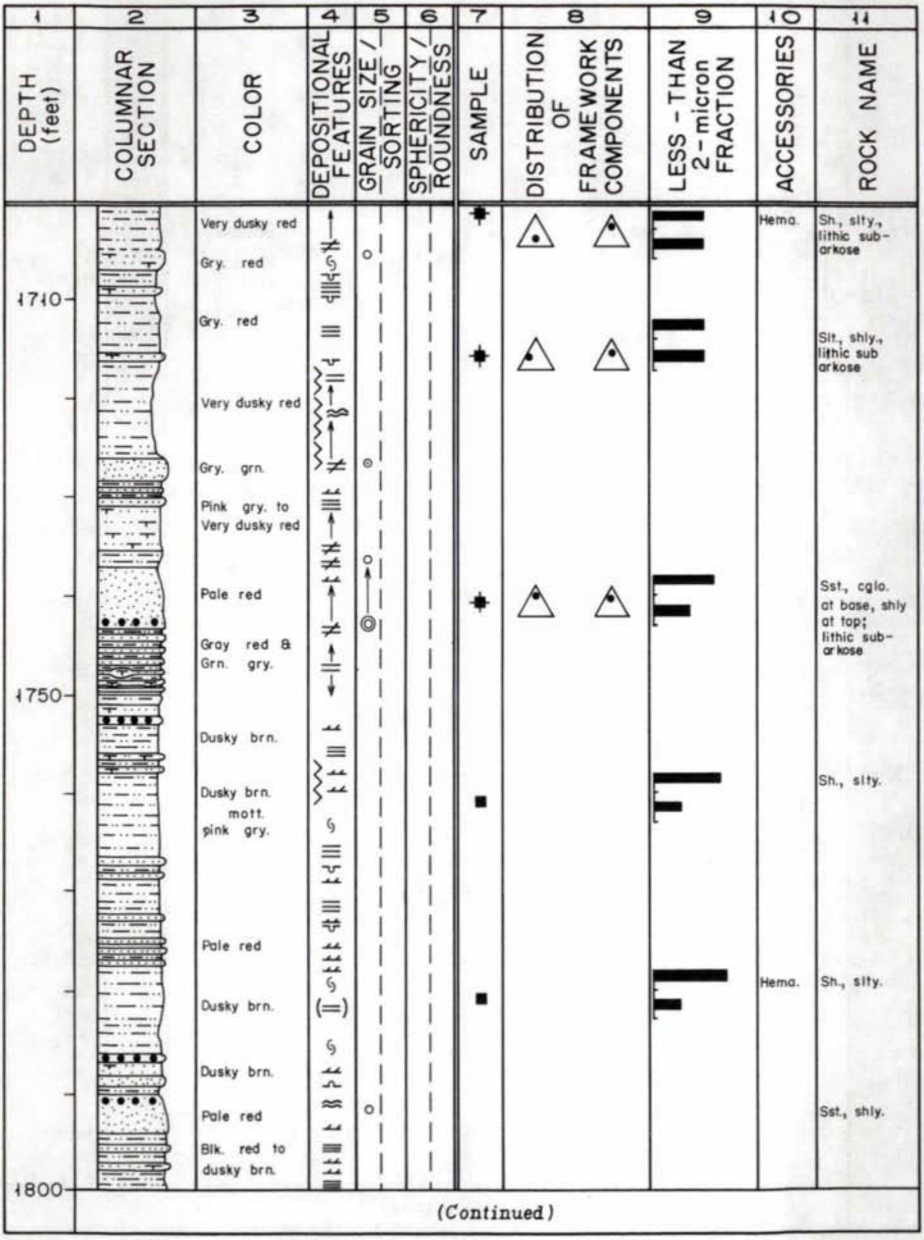


Figure B-1 -- Lithic log of diamond drill core Lonsdale 65-1 (cont.)

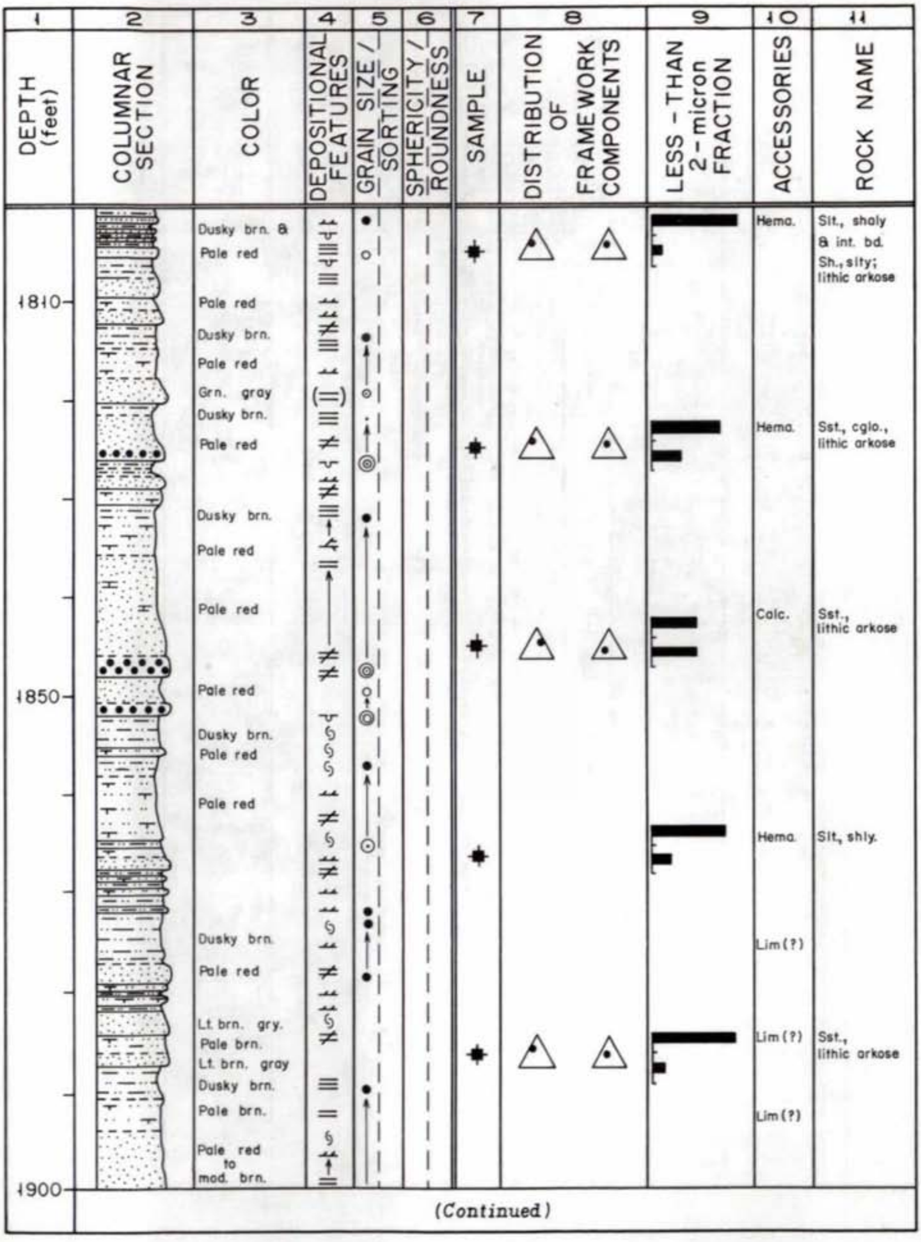


Figure B 1 — Lithic log of diamond drill core Lonsdale 65-1 (cont.)

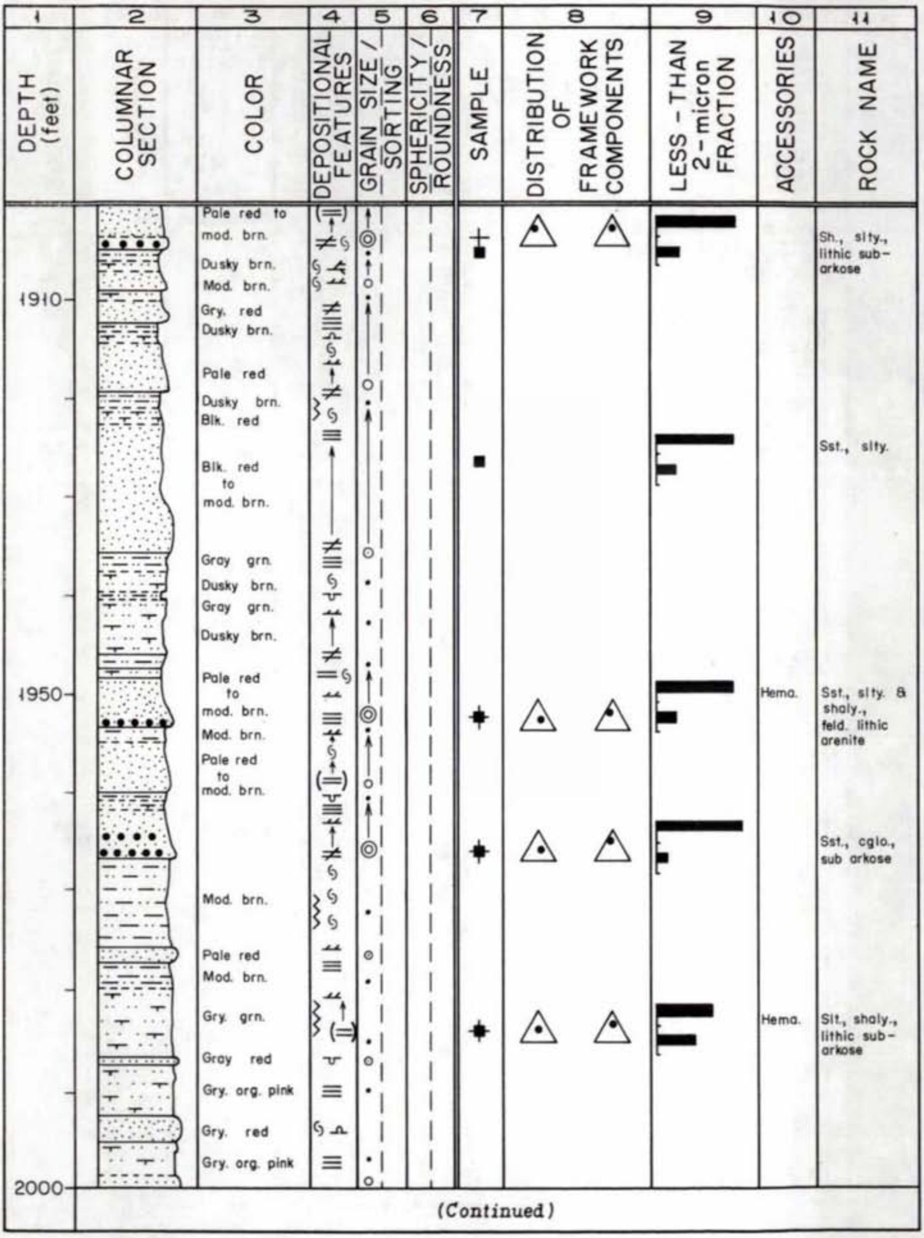


Figure B-1 -- Lithic log of diamond drill core Lonsdale 65-1 (cont.)

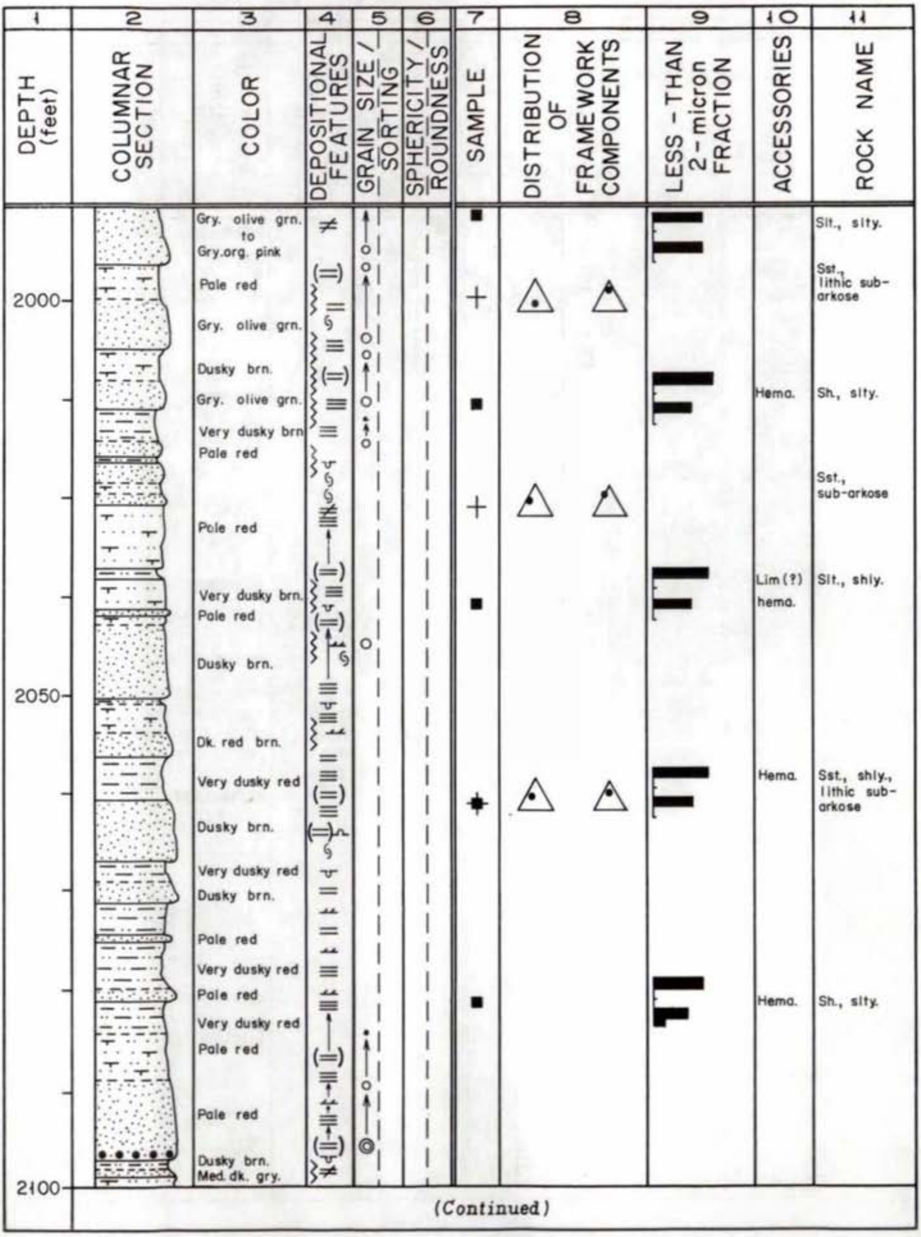


Figure B-1 — Lithic log of diamond drill core Lonsdale 65-1 (cont.)

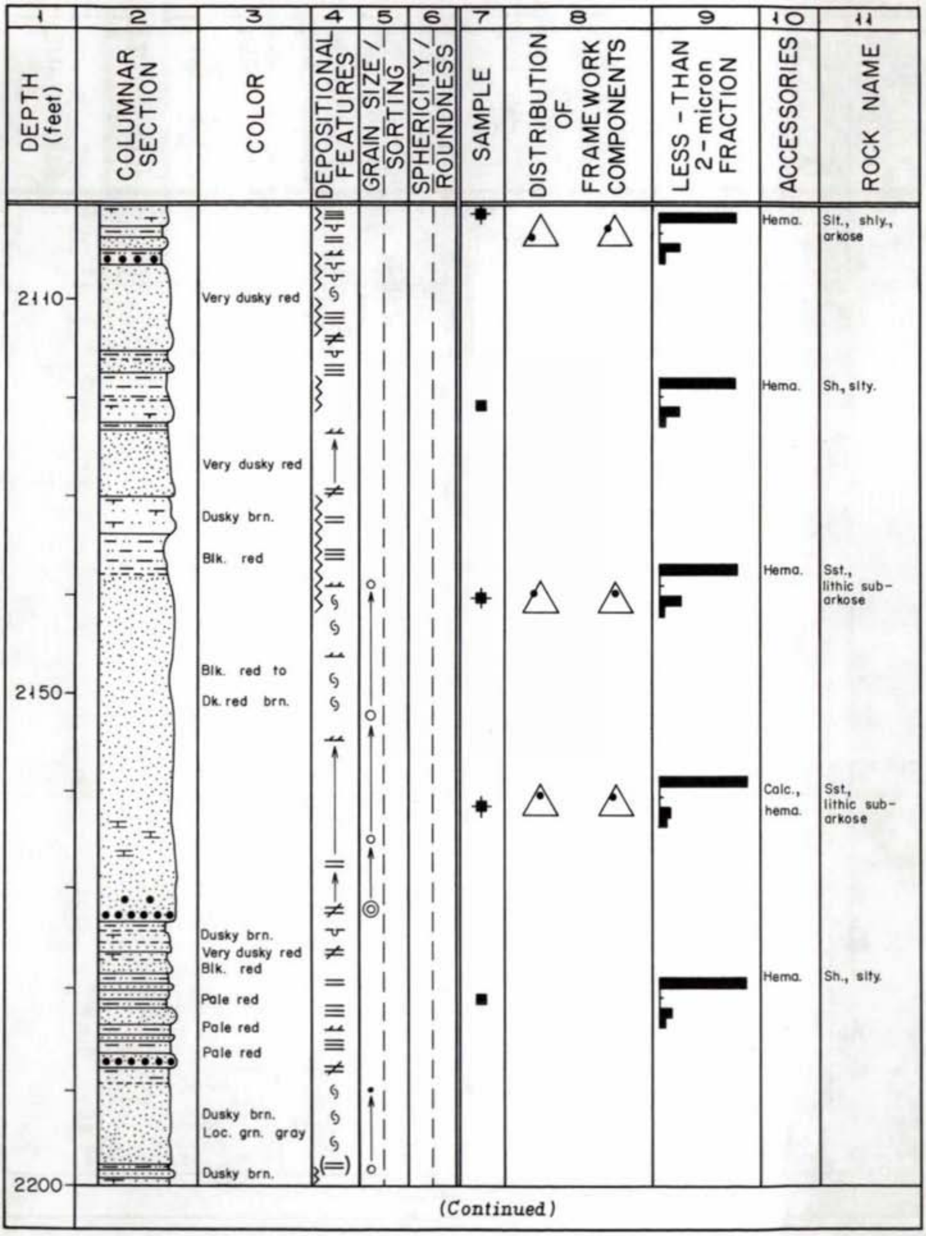


Figure B-1 — Lithic log of diamond drill core Lonsdale 65-1 (cont.)

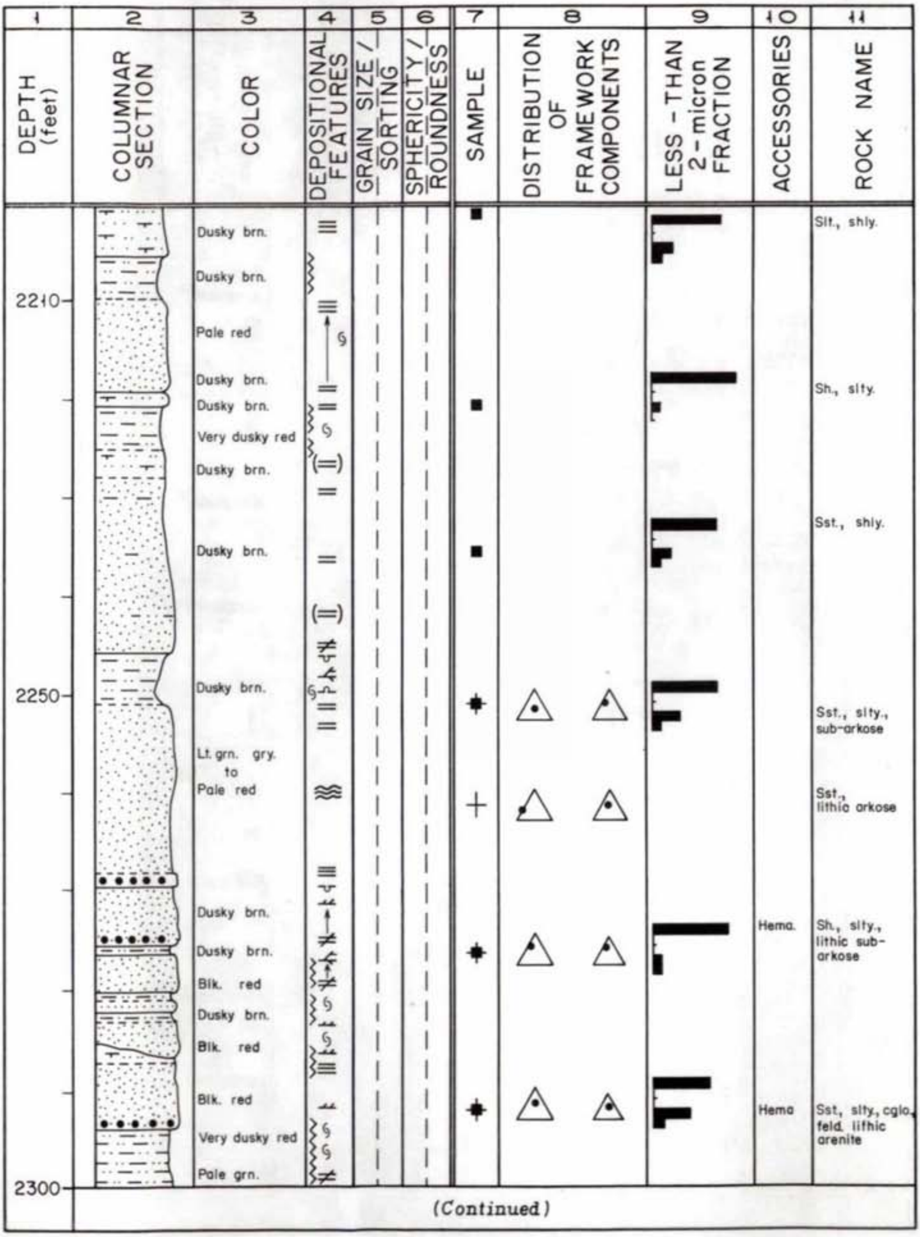


Figure B-1 — Lithic log of diamond drill core Lonsdale 65-1 (cont.)

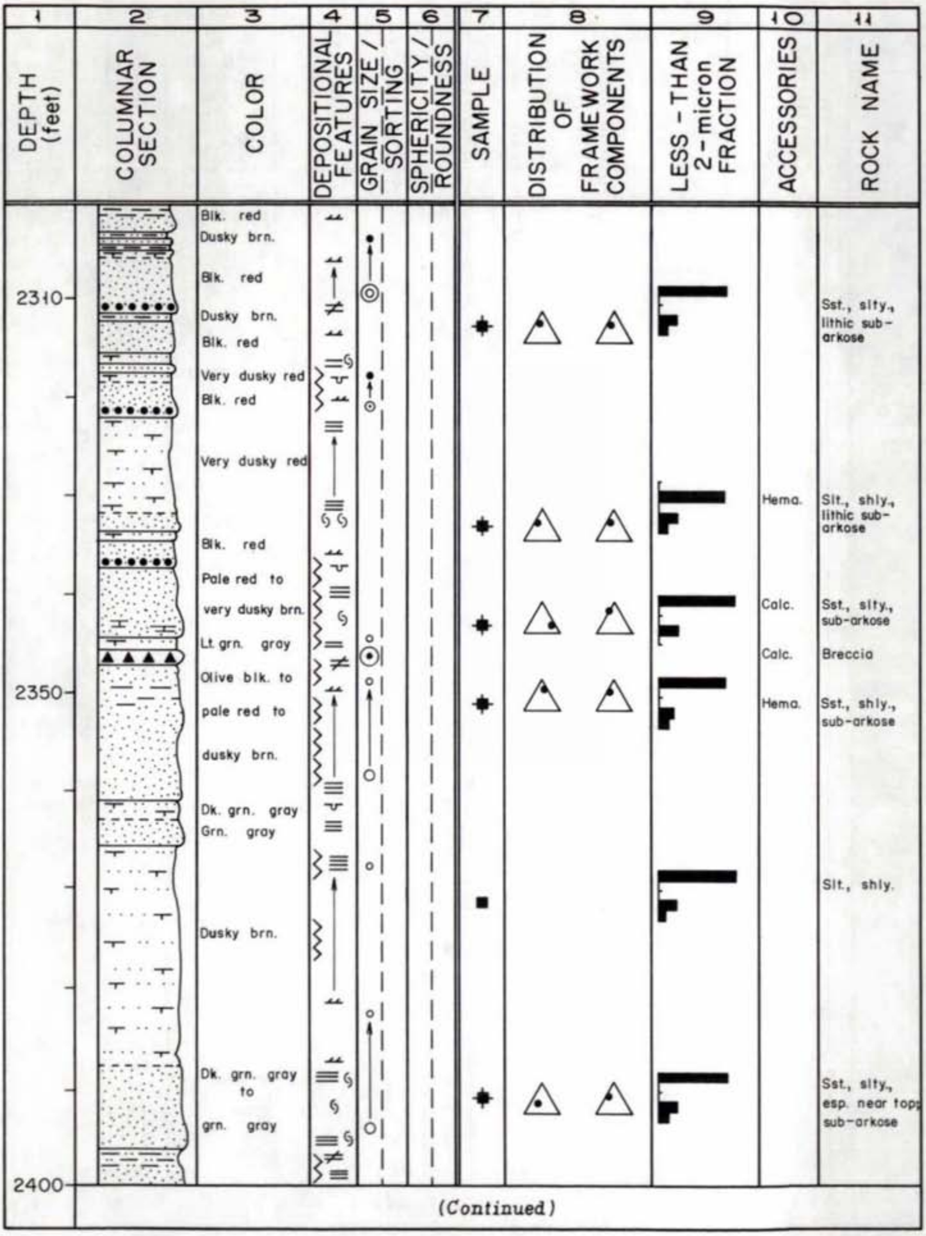


Figure B-1 — Lithic log of diamond drill core Lonsdale 65-1 (cont.)

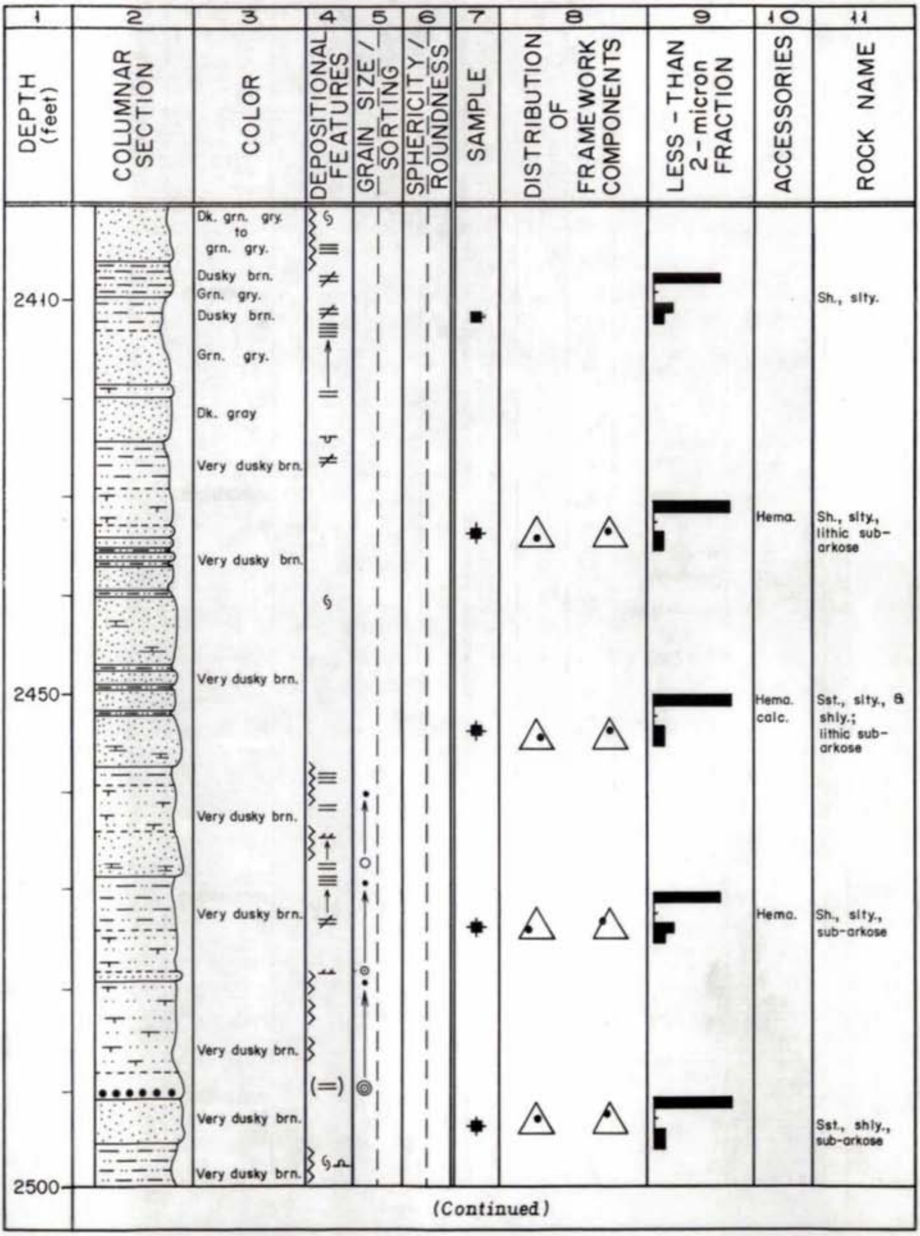


Figure B-1 — Lithic log of diamond drill core Lonsdale 65-1 (cont.)

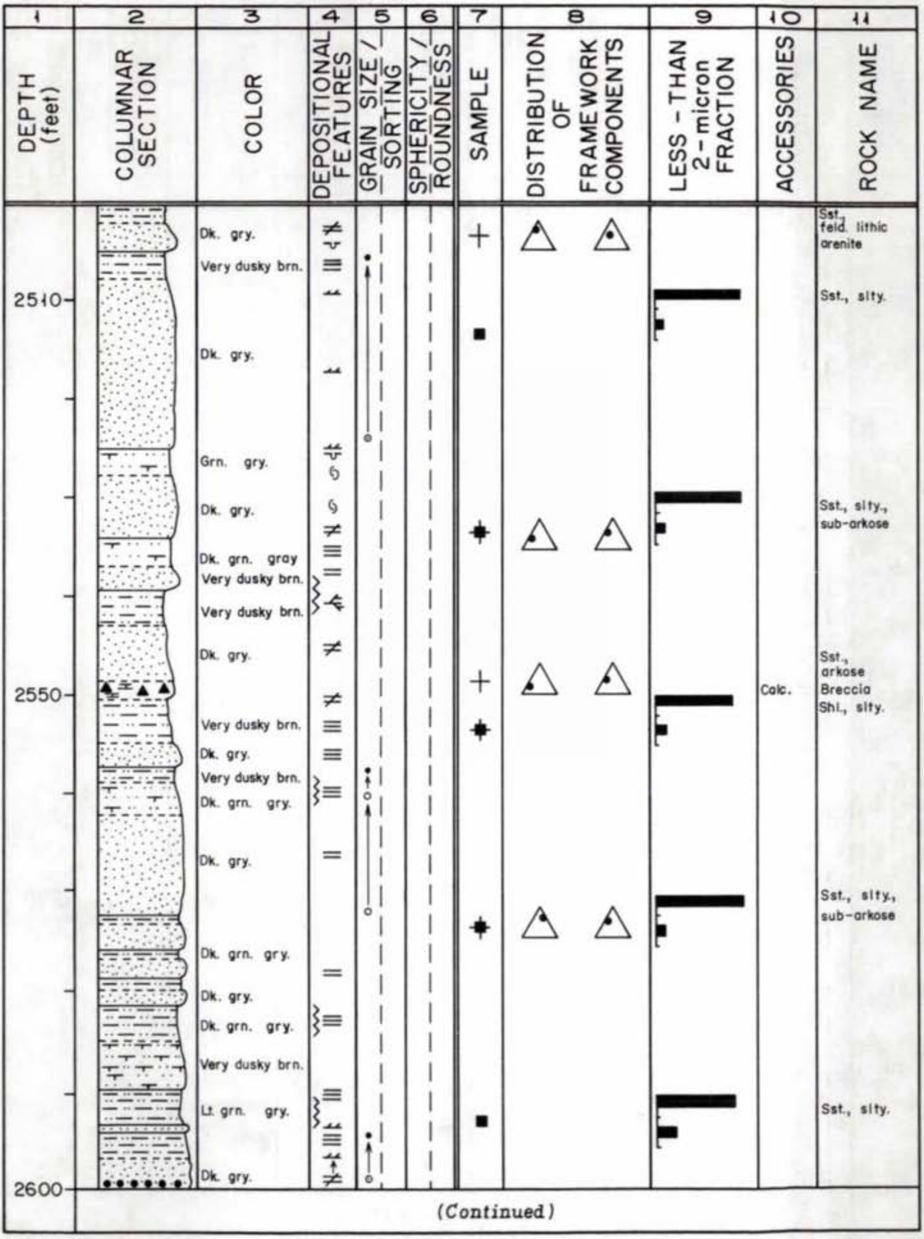


Figure B-1 -- Lithic log of diamond drill core Lonsdale 65-1 (cont.)

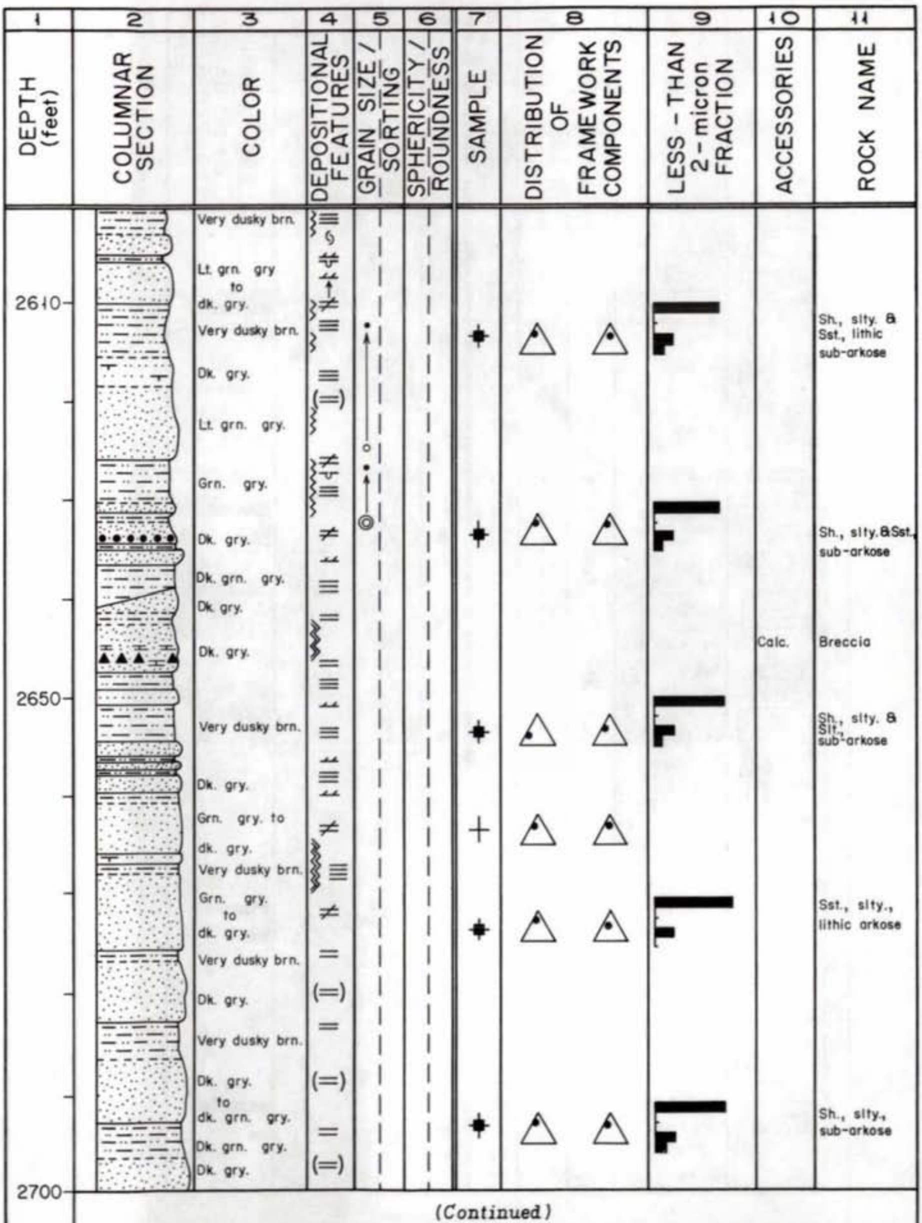


Figure B-1 — Lithic log of diamond drill core Lonsdale 65-1 (cont.)

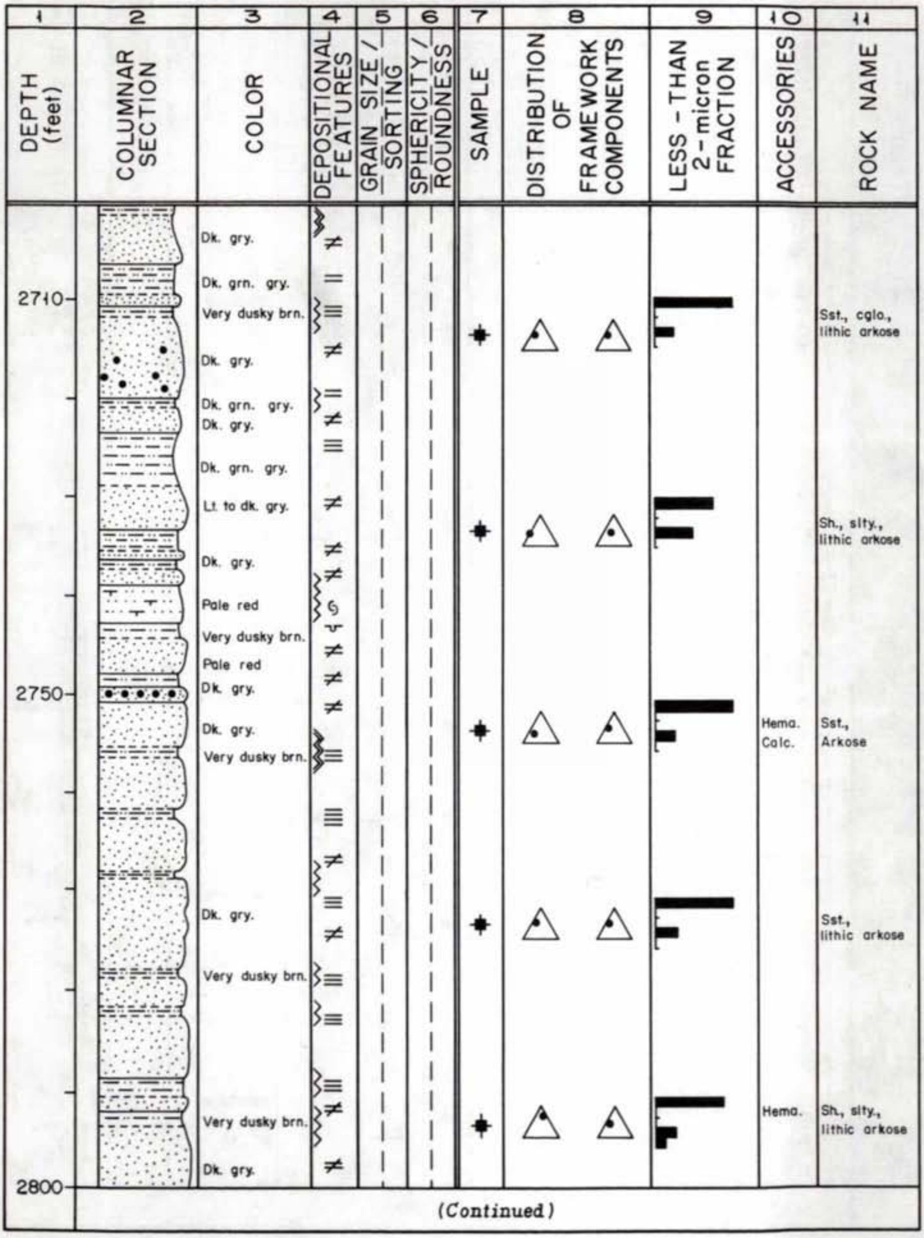


Figure B-1 — Lithic log of diamond drill core Lonsdale 65-1 (cont.)

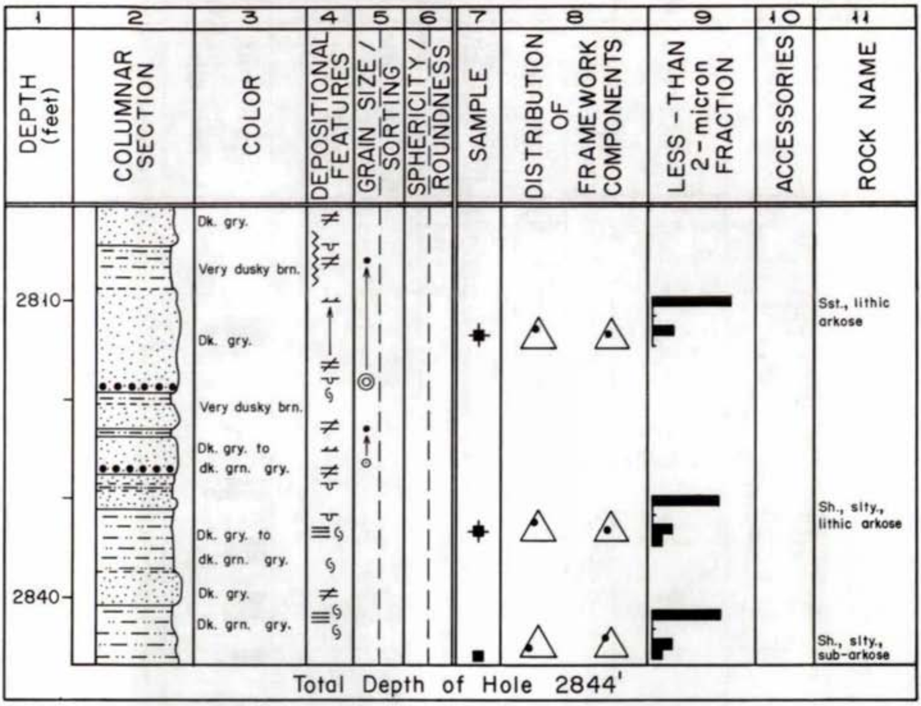


Figure B-2 -- Lithic log of diamond drill core Hampton 65-1

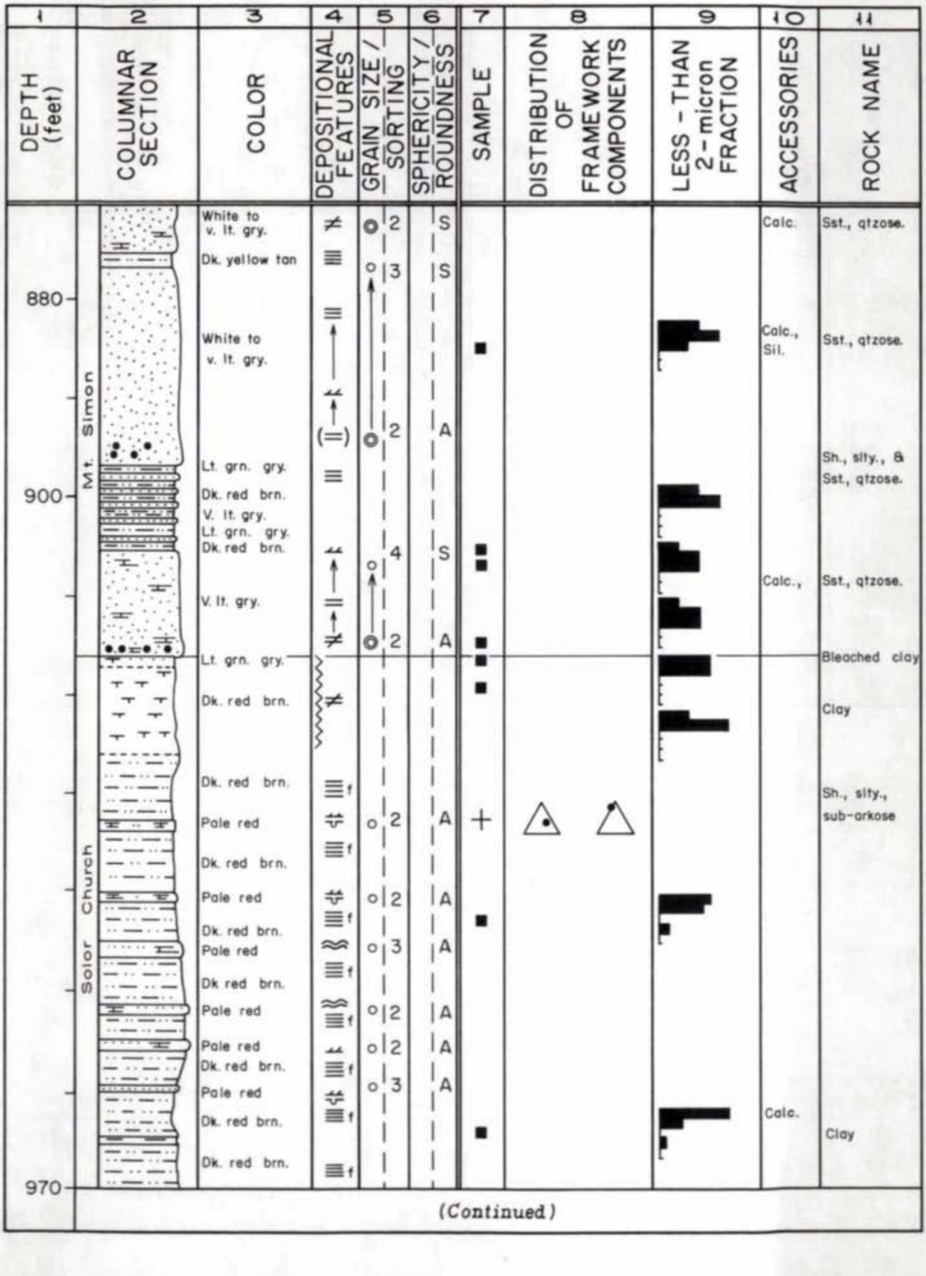


Figure B-2 — Lithic log of diamond drill core Hampton 65-1 (cont.)

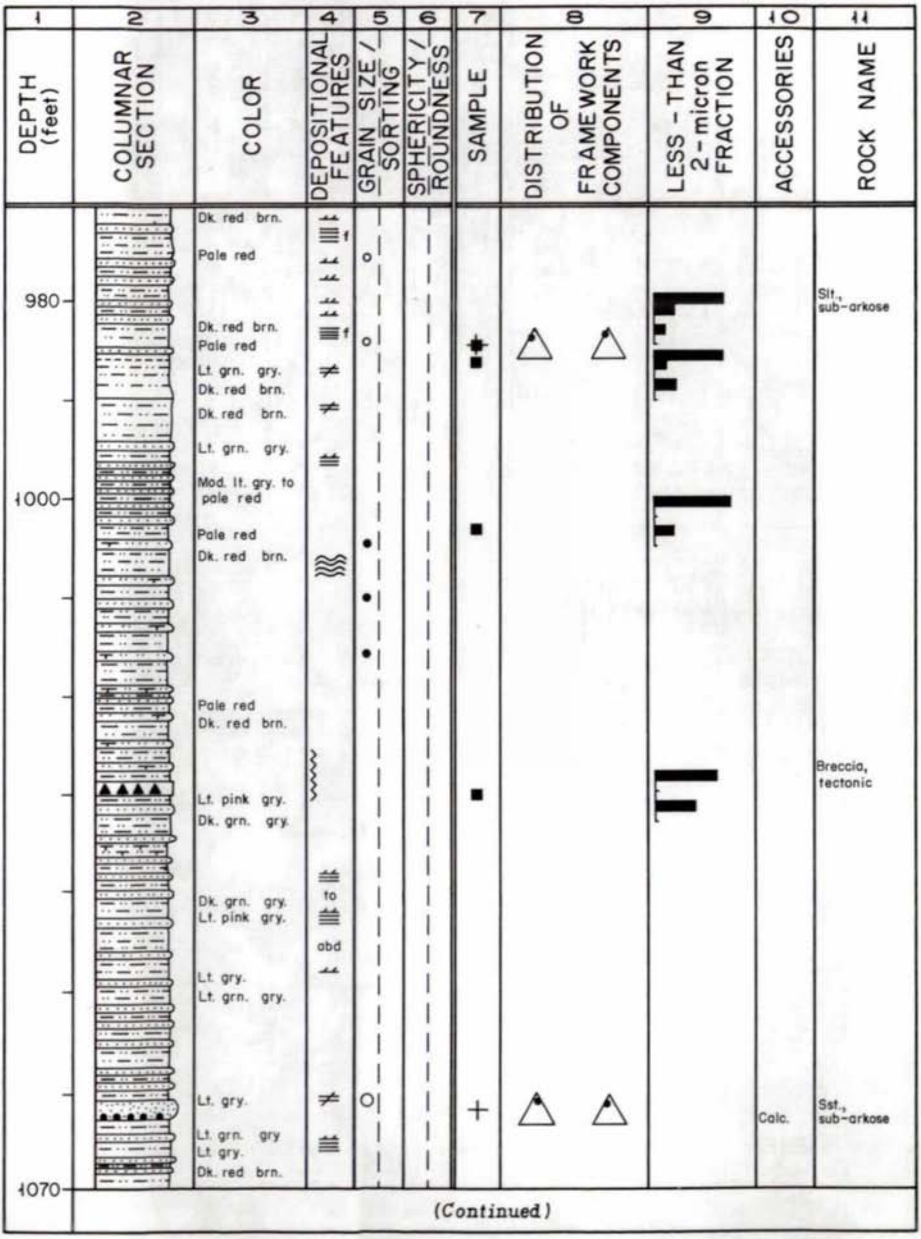


Figure B-2 — Lithic log of diamond drill core Hampton 65-1 (cont.)

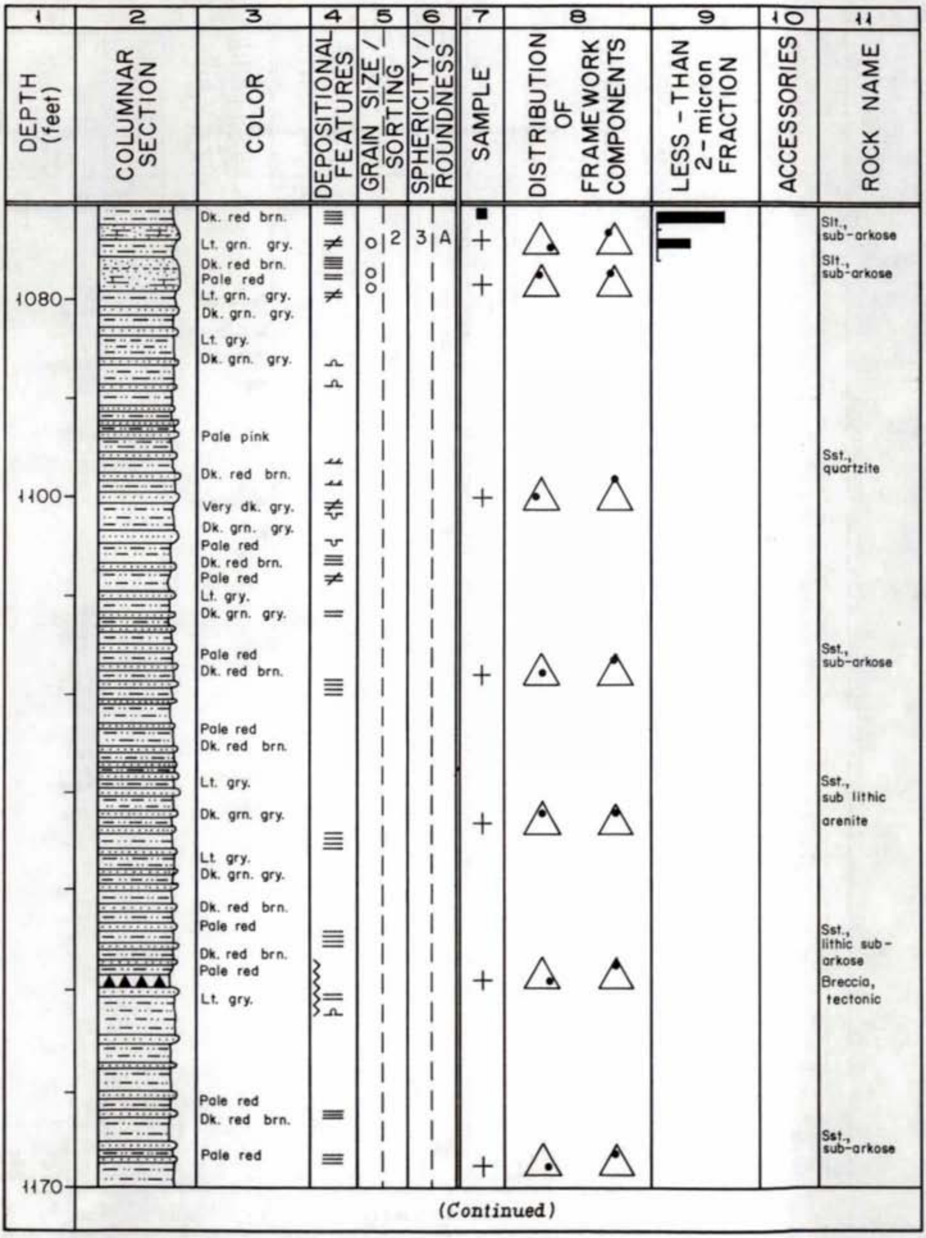


Figure B-2 — Lithic log of diamond drill core Hampton 65-1 (cont.)

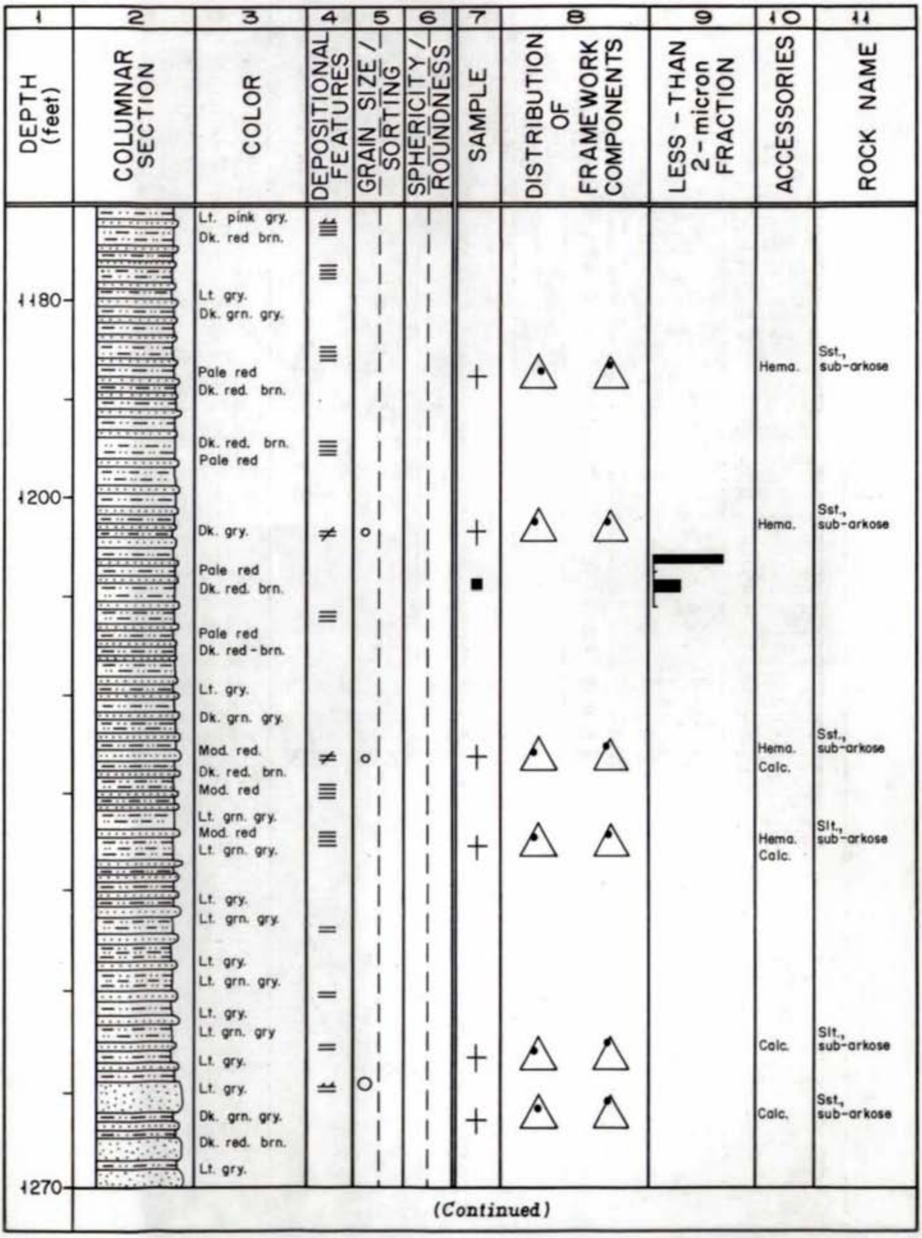


Figure B-2 — Lithic log of diamond drill core Hampton 65-1 (cont.)

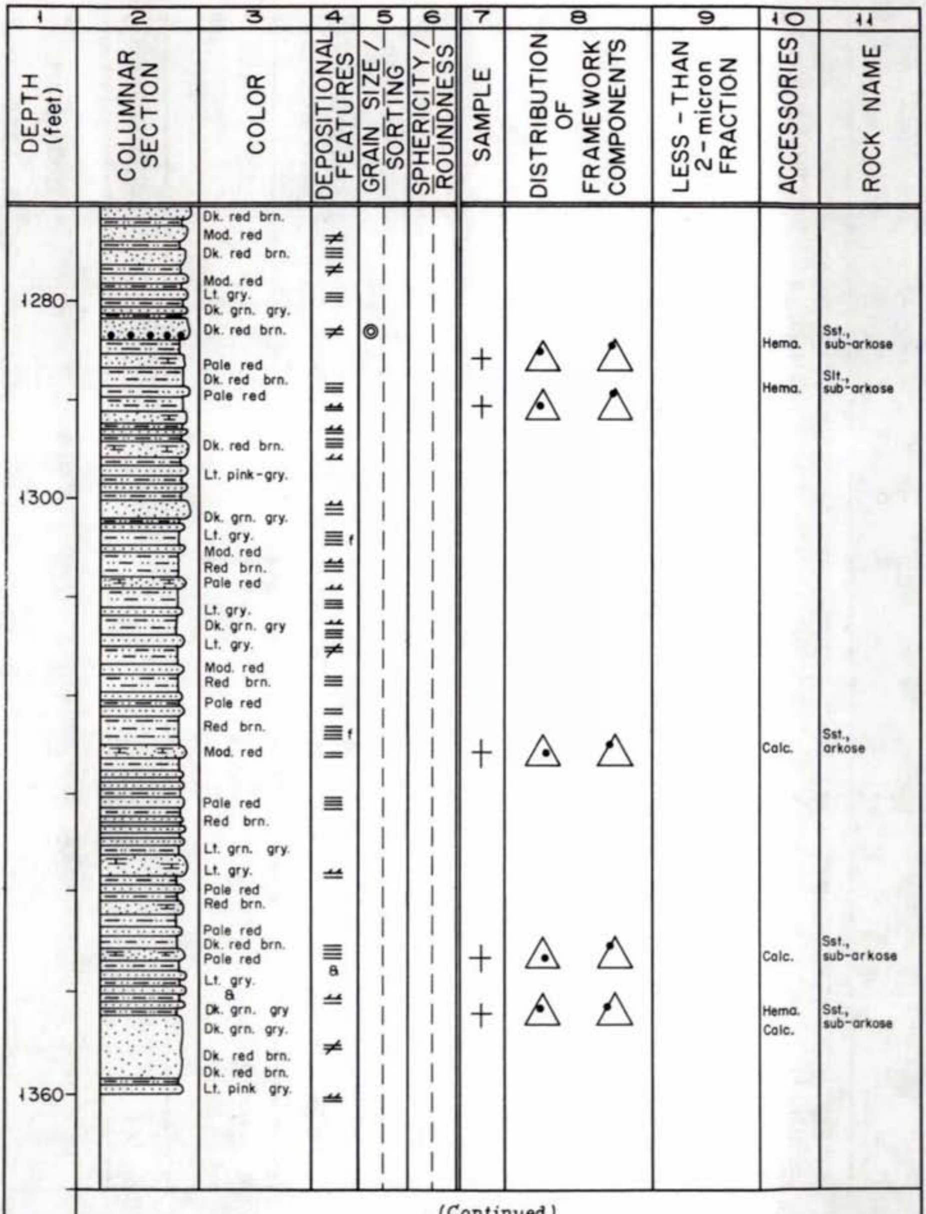


Figure B-2 — Lithic log of diamond drill core Hampton 65-1 (cont.)

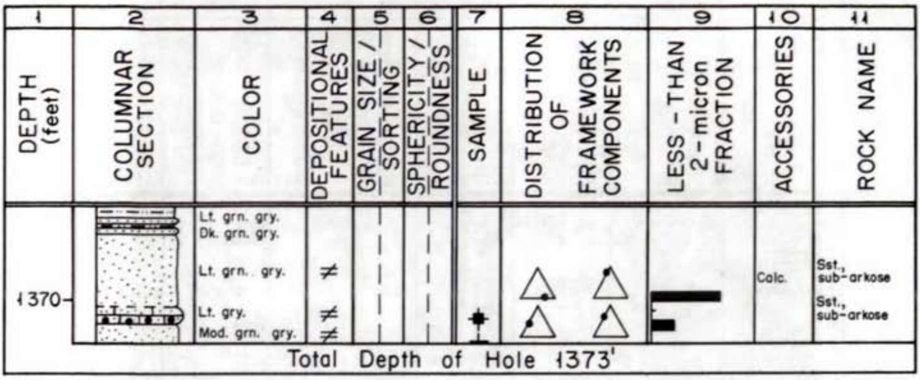


Figure B-3 — Lithic log of diamond drill core Vermillion 65-3

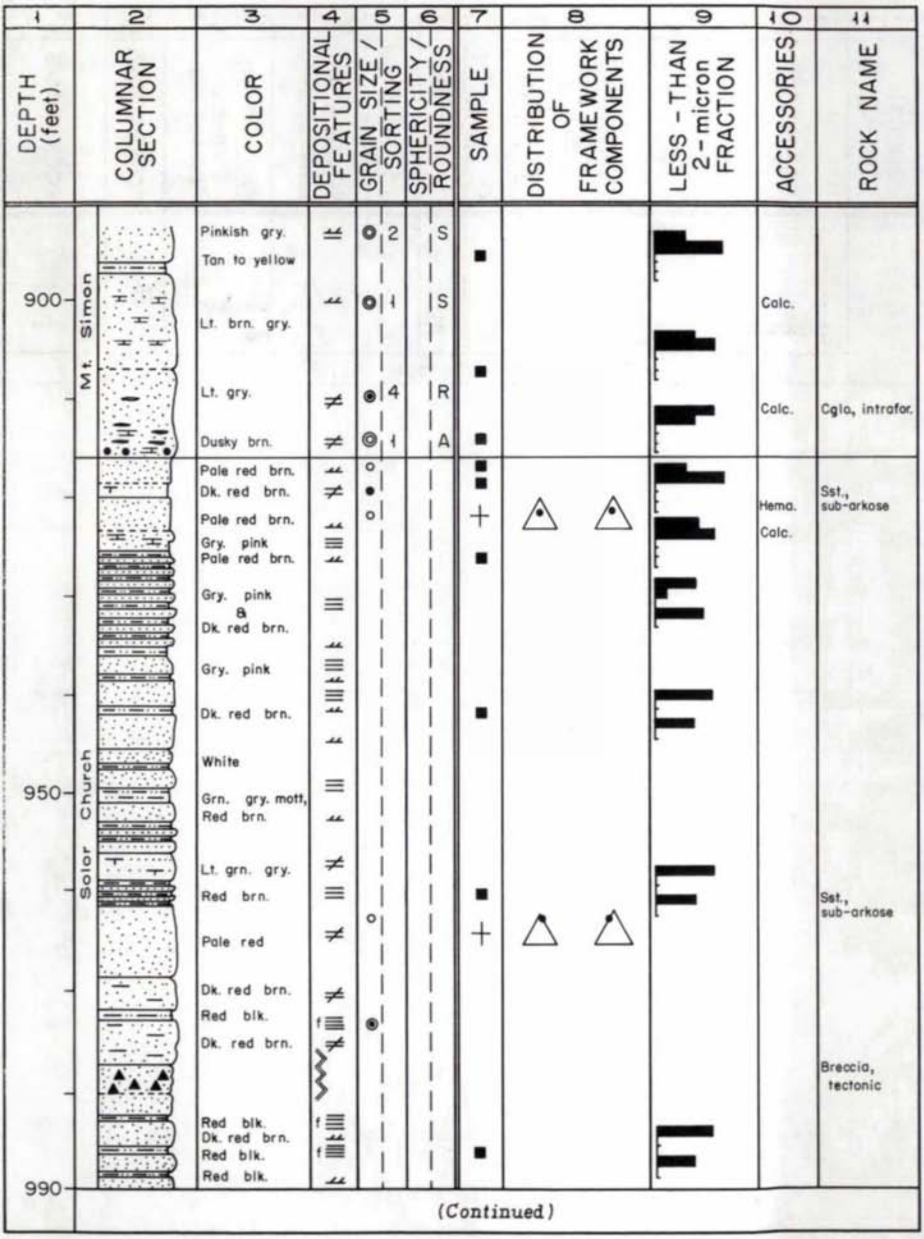


Figure B-3 -- Lithic log of diamond drill core Vermillion 65-3 (cont.)

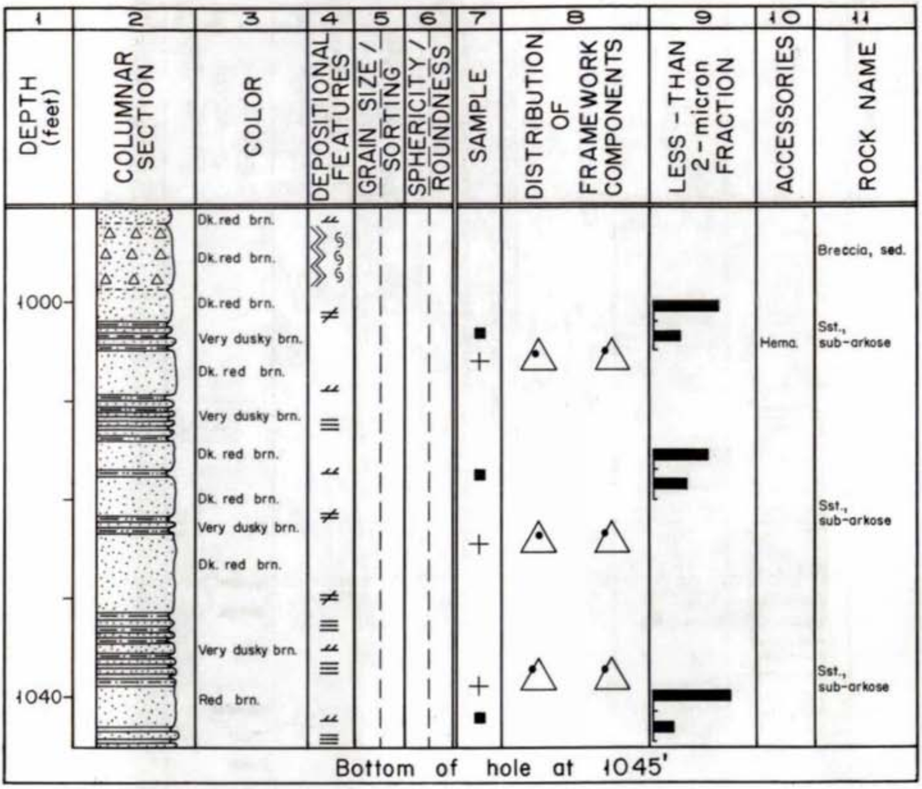


Figure B-4 - Lithic log of diamond drill core Vermillion 66-1

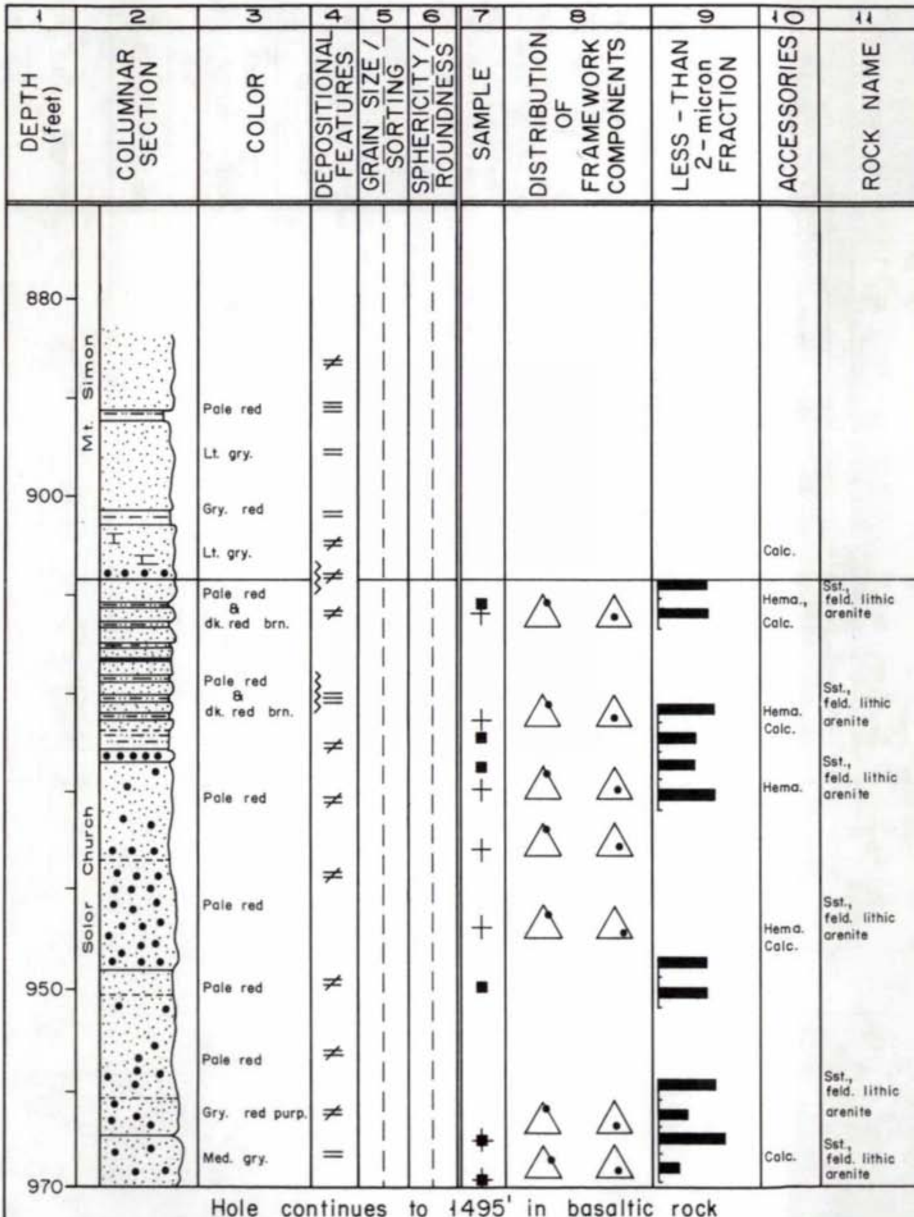


Figure B-5 — Lithic log of diamond drill core Vermillion 66-2

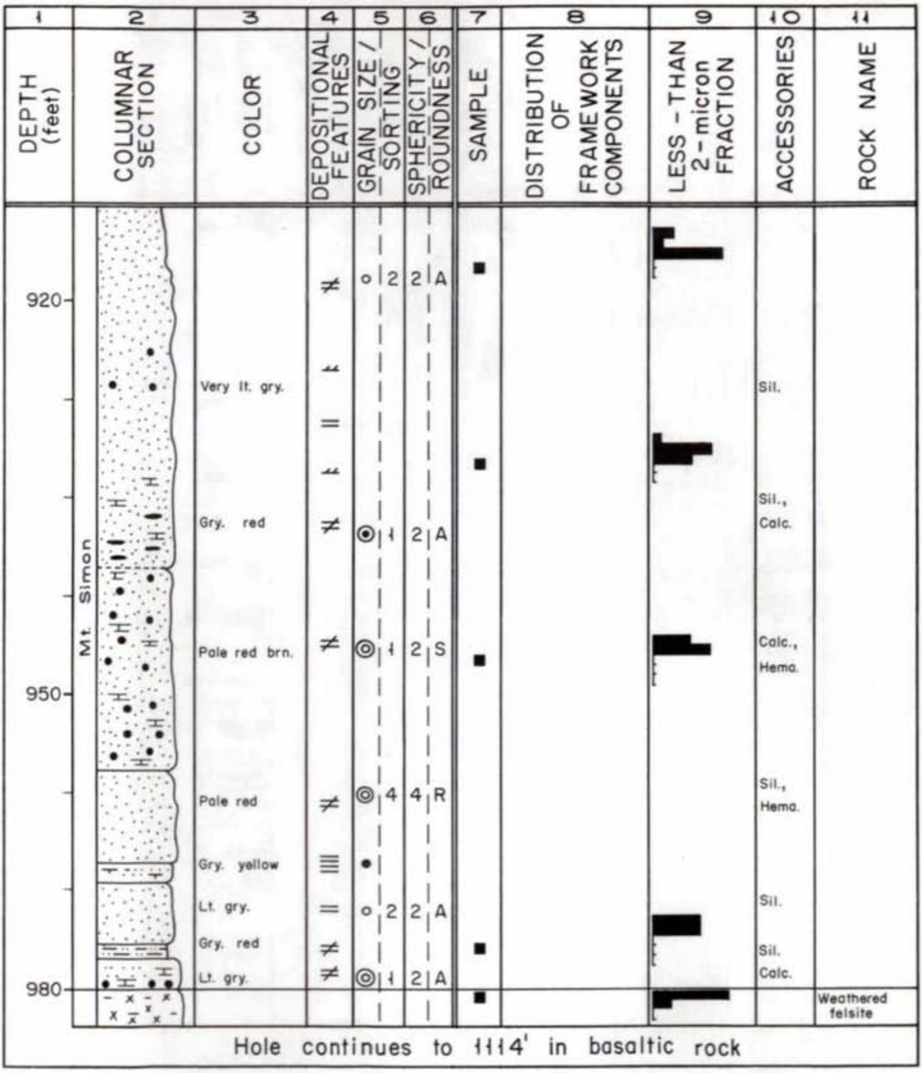


Figure B-6 — Lithic log of diamond drill core Vermillion 66-3

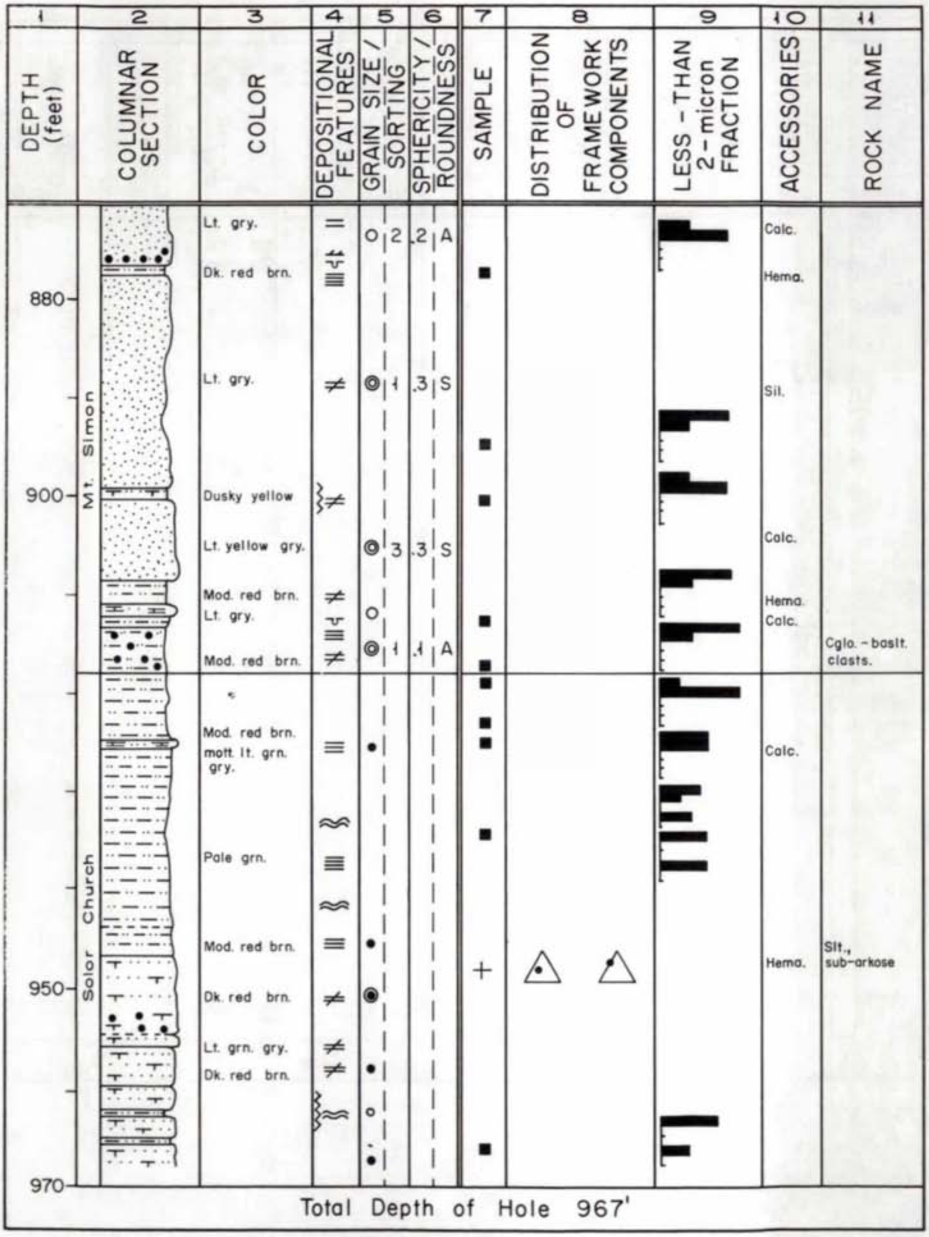


Figure B-7 -- Lithic log of diamond drill core Vermillion 66-4

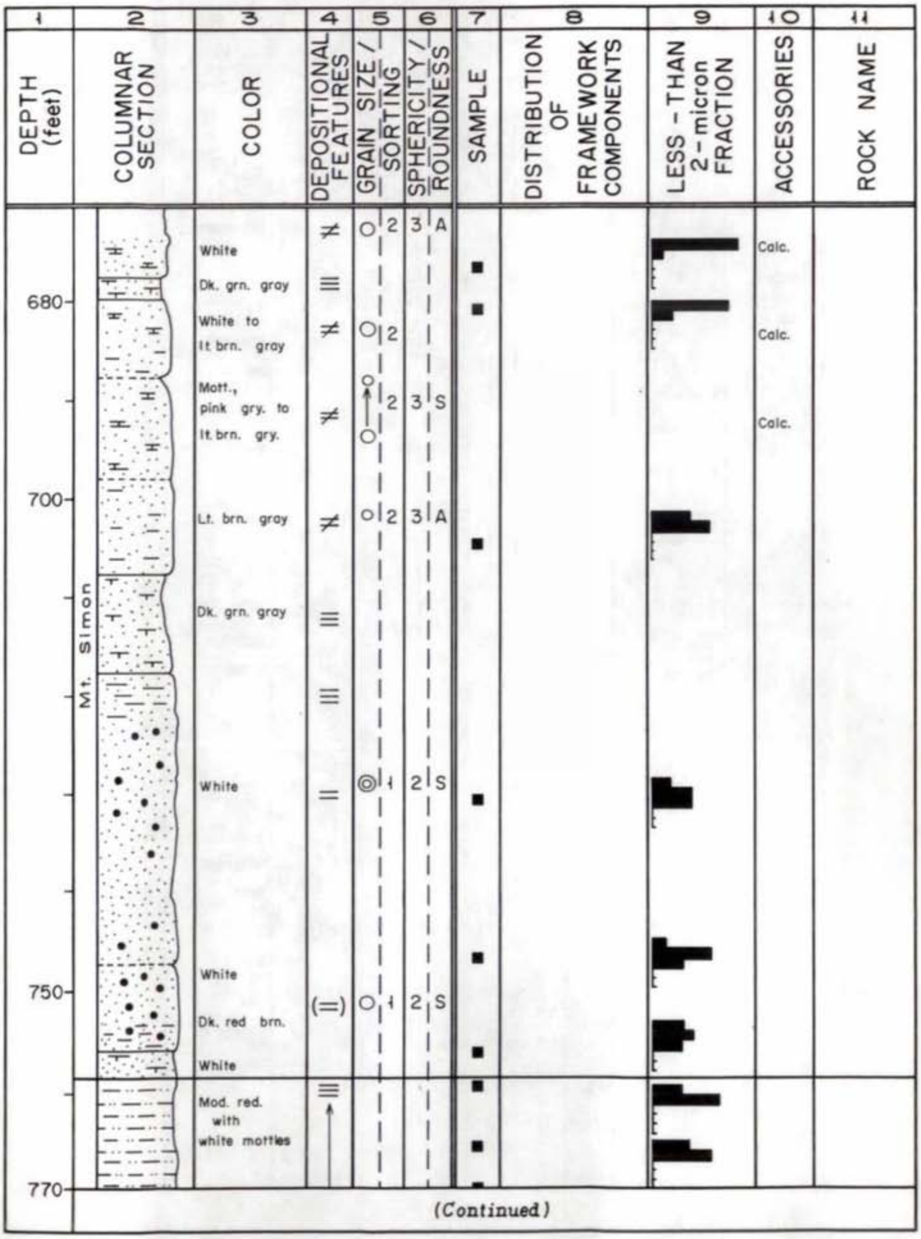


Figure B-7 -- Lithic log of diamond drill core Vermillion 66-4 (cont.)

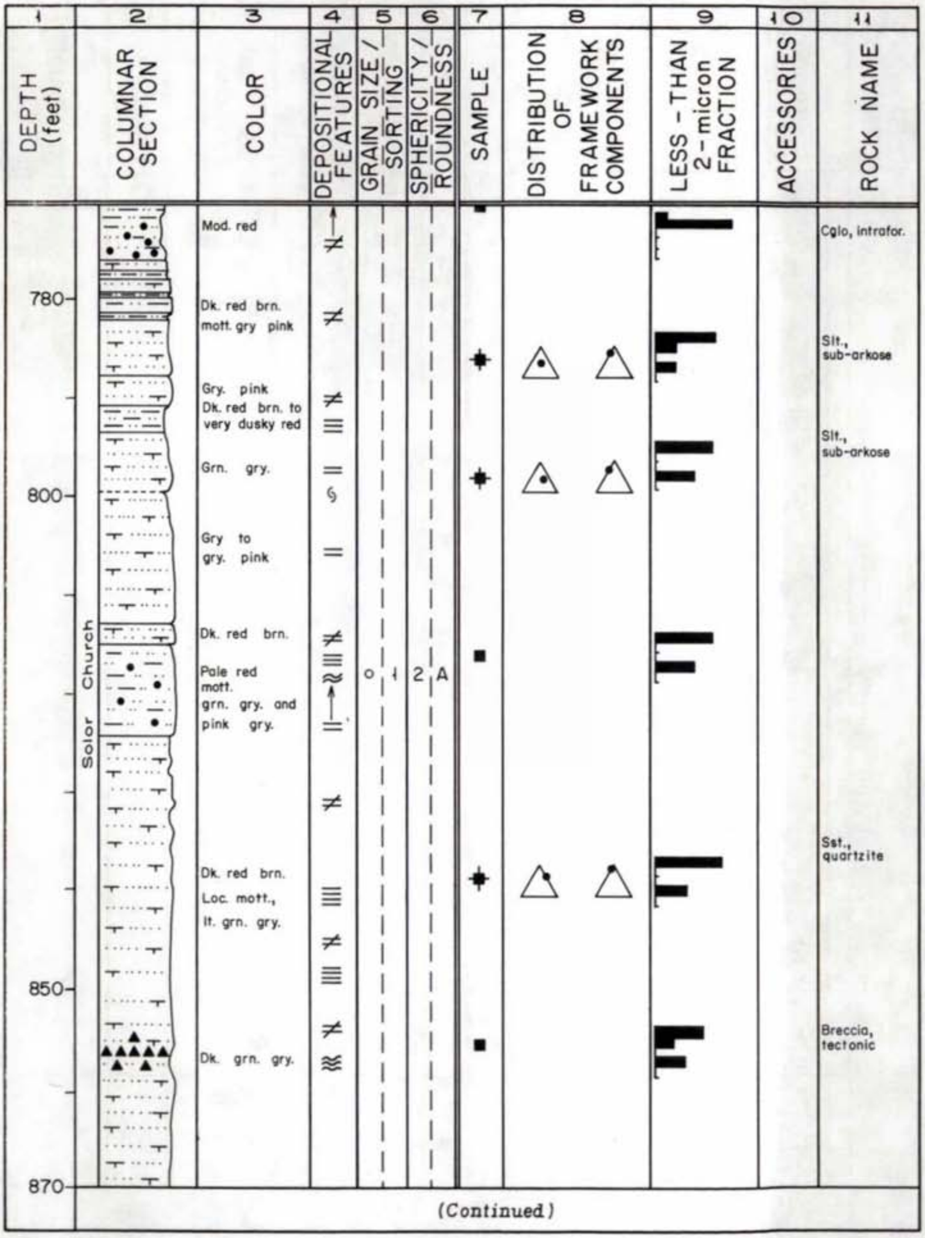


Figure B-7 — Lithic log of diamond drill core Vermillion 66-4 (cont.)